

NASA CR-135273
PWA-5547-4



PHASE IV Final Report

Advanced Supersonic Propulsion Study

(NASA-CR-135273) ADVANCED SUPERSONIC PROPULSION STUDY, PHASE 4 Final Report (Pratt and Whitney Aircraft Group) 109 p HC A06/MF A01	N78-11062 CSCL 21E G3/07	Unclas 52366
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Commercial Products Division
Pratt & Whitney Aircraft Group
United Technologies Corporation

Prepared for

National Aeronautics and Space Administration

NASA Lewis Research Center
NAS3-19540



1 Report No. NASA CR- 135273	2 Government Accession No.	3 Recipient's Catalog No.	
4 Title and Subtitle ADVANCED SUPERSONIC PROPULSION STUDY PHASE IV FINAL REPORT		5 Report Date September 1977	
		6 Performing Organization Code	
7. Author(s) R. A. Howlett and F. D. Streicher		8 Performing Organization-Report No. PWA-5547-4	
		10 Work Unit No.	
9 Performing Organization Name and Address Commercial Products Division Pratt & Whitney Aircraft Group United Technologies Corporation - East Htfd., CT		11 Contract or Grant No. NAS3-19540	
		13. Type of Report and Period Covered Contractor Report	
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		14 Sponsoring Agency Code	
15 Supplementary Notes Project Manager, Dr. Edward A. Willis, Jr. Flight Performance Section NASA Lewis Research Center, Cleveland, Ohio			
16 Abstract Continuation of the NASA/P&WA study to evaluate various propulsion system concepts for advanced supersonic cruise aircraft concentrated on integration studies of the most promising engine concepts. These studies were performed jointly by P&WA and the Supersonic Cruise Airplane Research (SCAR) Contractors; the Boeing Commercial Airplane Company, the Douglas Aircraft Company, and the Lockheed California Company. For the most promising engine concept, the Variable Stream Control Engine (VSCE), installation characteristics were evaluated for the three advanced supersonic airplane designs being evaluated by the SCAR contractors. Sensitivity of the VSCE concept to change in technology projections was evaluated in terms of impact on overall installed performance. Based on these sensitivity results, critical technology requirements were reviewed, resulting in the reaffirmation of the following requirements: low-noise nozzle system; a high performance, low emissions duct burner and main burner; hot section technology; variable geometry components; and propulsion integration features, including an integrated electronic control system. This report summarizes the work accomplished under Phase IV of the Advanced Supersonic Propulsion Study. Also, critical technology areas are described that relate to the VSCE concept, and required programs are summarized.			
17 Key Words (Suggested by Author(s)) Advanced Supersonic Propulsion Technology Variable Stream Control Engine Variable Cycle Engine Low-Emissions Duct Burner Low-Noise Coannular Nozzle		18 Distribution Statement	
19 Security Classif (of this report) UNCLASSIFIED	20. Security Classif (of this page) UNCLASSIFIED	21. No. of Pages 113	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

This report summarizes a contracted study of advanced supersonic propulsion systems conducted for NASA by Pratt & Whitney Aircraft with The Boeing Company, Douglas Airplane Company and Lockheed California Company as subcontractors. This study, referred to as Phase IV, was conducted during the period mid 1976 to mid 1977. It was a continuation of Phase I, reported in NASA CR-134633; Phase II, reported in NASA CR-134904; and Phase III, reported in NASA CR-135148.

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1.0 SUMMARY

The National Aeronautics and Space Administration (NASA) is engaged in a study of the application of advanced technology to long range, supersonic, commercial transport aircraft under the Supersonic Cruise Airplane Research (SCAR) program. As part of this program, P&WA has been conducting advanced supersonic propulsion studies with the overall objective of identifying the most promising advanced engine concepts and related technology programs necessary to provide a sound basis for design and possible future development of an advanced supersonic propulsion system. These studies were conducted in four phases. This report documents the Phase IV study program. Pratt & Whitney Aircraft is continuing engine/airframe integration studies under subcontract to the SCAR airframe companies.

In the Phase I studies, a broad spectrum of conventional and unconventional propulsion systems were studied parametrically over a wide range of cycle variables. More concentrated parametric studies, including refined cycle studies, airplane integration studies, and initiation of preliminary design studies, were conducted during Phase II and identified the Variable Stream Control Engine (VSCE) and a single rear-valve Variable Cycle Engine (VCE) as the most promising concepts. Parametric refinement studies and preliminary design were continued in Phase III resulting in the VSCE being identified as the most promising engine concept for advanced commercial aircraft.

Consequently, the Phase IV engine/airframe integration studies concentrated on the VSCE concept. In this effort, P&WA subcontracted studies to the Boeing Commercial Airplane Company, the Douglas Aircraft Company and the Lockheed California Company to determine the installation requirements and performance characteristics of the VSCE in the three different advanced airplane designs being evaluated by the airplane contractors. The VSCE was refined and matched to meet the installation requirements of each airplane company.

Because of its design flexibility, the VSCE successfully meets the installation requirements of each advanced airplane design, especially in the following areas:

- Inlet/engine airflow matching,
- Compatibility with either structural or conventional nacelle,
- Contoured engine envelope enabling accessories to be located without compromising nacelle design,
- Capability for programmed throttle scheduling to optimize the coannular noise benefit during takeoff,
- Nozzle/reverser system adaptability to targeting and other operational requirements,
- Capability of being scaled to a range of sizes without compromising the basic design.

As part of the Phase IV integration study, technology sensitivity of the VSCE and the rear-valve VCE was evaluated. Although preceding studies had shown the rear-valve VCE to be less attractive in noise and performance than the VSCE, the rear-valve VCE was included in the study to determine if different technology levels would alter the relative position between the two VCE concepts. The technology sensitivity study was made in two ways. The first approach was to consider nearer-term technology and reoptimize the engines for the earlier technology. The second method was to evaluate the impact of not meeting critical technology goals during a development program. For this second approach, the engines were not re-optimized, as they were for the first approach, but were rematched to minimize the effect of missing the selected technology goals.

As a result of these technology sensitivity studies, the VSCE concept was shown to be capable of being redefined for nearer-term technology without severely compromising its installed performance characteristics. Based on the results from these technology sensitivity studies, work on the rear-valve VCE was discontinued since it did not perform as well as the VSCE for either technology level and is a more complex engine concept.

Sensitivity of the VSCE to missing technology goals shows that the coannular noise benefit and exhaust nozzle performance have the most significant effect on airplane range and, therefore, these nozzle characteristics cannot be compromised or traded for other requirements without severe system penalties. Turbine materials hot section cooling technology, and duct burner efficiency are the next most critical technology areas of the VSCE.

A review of the critical technology requirements for the VSCE concept was conducted, resulting in a reaffirmation of the requirements identified in the Phase III study. These requirements are: low noise, high performance coannular nozzle; low emissions, high performance duct burner; variable geometry components including the inlet, fan, compressor and nozzle/reverser/ejector system; low emissions, high temperature primary burner; hot section cooling and materials technology; and full authority electronic control system.

Follow-on studies to continue refinement of the VSCE are recommended as follows:

- Preliminary design of the VSCE,
- Preliminary design of the integrated VSCE propulsion system.

Continuation of the joint engine/airplane company integration studies is recommended in the following areas:

- Preliminary design of nozzle/reverser system,
- Preliminary design of engine/airframe interface systems, especially thermal management of fuel/air/oil systems,
- Continued evaluation of programmed throttle schedule for noise abatement.
- Preliminary design of inlet/engine.

2.0 INTRODUCTION

Pratt & Whitney Aircraft has been conducting advanced supersonic propulsion studies under NASA contracts NAS3-16948 (Phases I and II) and NAS3-19540 (Phase III and Phase IV). The overall objective of this study is to identify technology programs necessary to provide the basis for design and possible future development of an advanced supersonic propulsion system.

2.1 BACKGROUND

Phase IV of P&WA's advanced supersonic propulsion studies has evolved from broad parametric studies of a large number of engine concepts in Phases I and II through refinement of the most promising concepts in Phase III. Phase I consisted of broad parametric studies to evaluate conventional and unconventional engine concepts, assessment of a H_2 fueled supersonic transport and an evaluation of the impact of advanced technology versus current technology on selected engines. The Phase I study showed that noise constraints have a major impact on selection of engine types and cycle parameters. It was also shown that an advanced supersonic commercial transport would benefit appreciably from the application of advanced engine technology in terms of improved system economics and lower noise levels.

As the study progressed into Phase II, refined parametric studies concentrated on the most promising concepts from Phase I: the Variable Stream Control Engine (VSCE) concept, an advanced derivative of a duct burning turbofan, and other Variable Cycle Engine (VCE) concepts that use valves to vary the cycle. Phase II included a parametric integration study to determine the overall engine/airplane performance and environmental characteristics of these concepts, and initiation of preliminary design studies. The VSCE and a single rear-valve VCE concept emerged as the most promising engines from Phase II. One of the most promising improvements for these concepts is the potential noise benefit associated with two stream coannular nozzles. Depending on the flexibility of each VCE concept, this noise benefit can be optimized by independently controlling the temperature and velocity conditions of these coannular flow streams.

Phase III studies continued the trend of refining and improving the preliminary design of the most promising engine concepts. Results of the intensive refinement effort of the VSCE and rear-valve VCE indicated the VSCE to be the most promising engine for advanced supersonic commercial aircraft. One of the key features of the VSCE contributing to its overall advantage relative to other engines is its capability to achieve the inverted exhaust velocity profile (fan duct stream exhaust velocity greater than core exhaust velocity) necessary to take advantage of the coannular noise benefit during take-off.

References 1, 2 and 3 are the final reports summarizing the Phase I, II and III studies.

2.2 DESCRIPTION OF PHASE IV STUDY TASKS

Phase IV was a continuation of Task B (Airframe Related Studies) conducted under Phase III. In Phase IV, P&WA provided subcontracts to the Boeing Commercial Airplane Company, the Douglas Aircraft Company and the Lockheed California Company to perform engine/nacelle/airframe integration studies. Based on the results from each SCAR contractor's

program, the VSCE concept was selected for evaluation. This selected engine was optimized for maximum compatibility with the airplane design and mission requirements of each airframe contractor. Coordination between P&WA and each contractor was required to adjust engine envelope dimensions, placement of accessories, customer connect points and load bearing capabilities to be compatible to the pod shape and location and other engine/airframe installation requirements. Engine definition and performance data were supplied to each airframe contractor. This included a nearer-term technology version of the VSCE and rear-valve VCE concepts.

Each airframe contractor determined the basic nacelle shape, location and drag characteristics which maximized the performance potential of the selected engine cycle, and the mission performance of the integrated engine/nacelle/airframe combination. The engines were sized to obtain optimum performance consistent with the FAR Part 36 noise constraint.

Based on these study results, joint P&WA/airframe contractor assessments of propulsion system technology requirements were prepared. The effect of not meeting critical technology projections was determined for the selected engine and was presented as a perturbation to the engine definition and airplane mission performance. Based on these results, the critical technology requirements and program recommendations from Phase III were reviewed and updated.

3.0 CONCLUSIONS AND RECOMMENDATIONS

The Supersonic Cruise Airplane Research (SCAR) study contractors, after evaluating the candidate Variable Cycle Engines, each identified the Variable Stream Control Engine (VSCE) as having the most potential for meeting the environmental and economic goals for advanced supersonic commercial aircraft. Based on these study results, the VSCE was unanimously selected for the engine/airplane integration studies and technology sensitivity study.

3.1 INTEGRATION STUDY

During the integration study, P&WA worked with each of the three SCAR contractors (The Boeing Commercial Airplane Company, Douglas Aircraft Company and Lockheed California Company) to determine the installation requirements of the VSCE in each of the advanced airplane designs. As a result of this effort, the VSCE definition was successfully matched to meet the installation requirements of all three airplane designs.

Flexibility in matching engine airflow capability to the inlet airflow supply over a wide range of power settings and operating conditions is a key feature of the VSCE. This flexibility enables it to match the airflow supplied by the inlets of all three airplane designs. Figure 3-1 illustrates the range of airflow schedules that can be matched by the VSCE and it shows that the inlet airflow schedules for each airplane design falls within the capability of the VSCE.

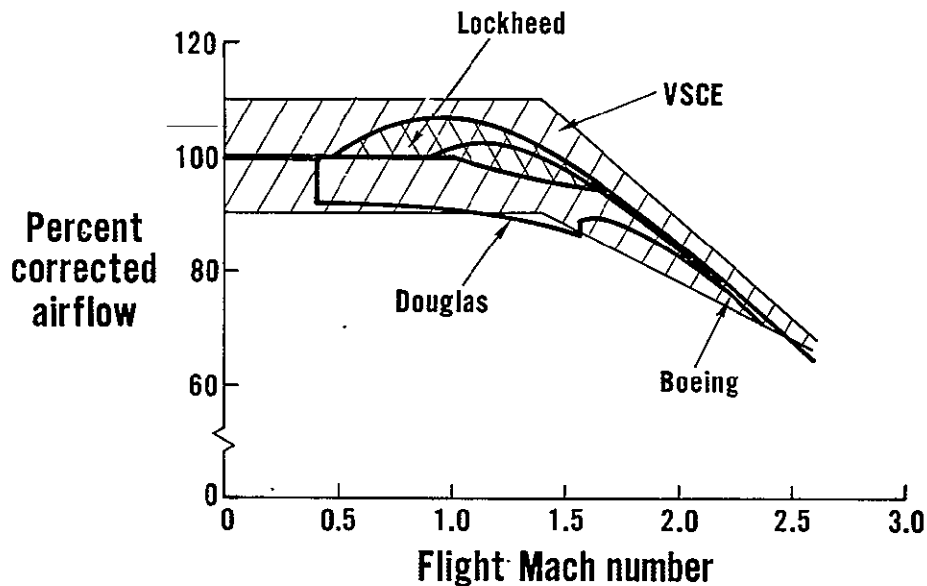


Figure 3-1 Range of Airflow Schedules That Can Be Matched By the Variable Stream Control Engine

The VSCE can be easily integrated with either a structural or a conventional nacelle with very little impact on the engine design. Because of the large outer engine case with its inherent strength, an inlet cowl can be mounted directly to the engine inlet case with less than a 45 kg (100 lbm) increase in engine weight. For the range of engine sizes being evaluated by the SCAR contractors, the VSCE is readily scaleable to suit each installation.

The contoured engine envelope of the VSCE provides a space in the area around the fan discharge case where engine accessories can be mounted without affecting the nacelle contours. The engine sizes presently being studied in conjunction with the engine accessory sizes have no adverse effect on the nacelle contour. However, the airframe accessories may affect the nacelle contours as the engines are scaled to the smaller sizes. For the pod arrangements with airframe accessories located around the engine, further study is required to minimize the effect on the pod contour.

During Phase IV, a simplified version of the ejector/reverser nozzle configuration was defined. Aft sliding panels replace the multihinge, actuated panel system defined in the Phase III nozzle study. Various patterns of targeting can be accomplished by selectively opening and closing these sliding panels. Targeting of the reversed airflow can be matched to prevent impingement on adjacent engines, on the fuselage or on the runway. There is, however, a length and weight penalty associated with this simpler nozzle design and more study is required to improve its overall characteristics.

Table 3-I summarizes the results of the integration study with Boeing, Douglas and Lockheed. As shown, the VSCE was matched to airplanes having cruise Mach numbers ranging from 2.2 to 2.6. The take-off airflow size of the VSCE resulting from the integration study ranged from 272 kg/sec (600 lbm/sec) to 342 kg/sec (754 lbm/sec) depending upon the specific airframe installation.

TABLE 3-I
INTEGRATION STUDY RESULTS

	Boeing	Douglas	Lockheed
Phase IV Study Engines	VSCE-502B VSCE-510 VSCE-511	VSCE-502B RVVCE-112C	VSCE-516 VSCE-516L
Design Mn	2.4	2.2	2.6
TOGW—kg (lbm)	340,190 (750,000)	340,190 (750,000)	269,890 (595,000)
VSCE size (takeoff airflow — kg/sec (lbm/sec))	318 (700)	342 (754)	272 (600)
Inlet type	Axisymmetric mixed compression	→	
Location of airframe accessories	Remote	→	Over/under engine
Range — km (n. mi.)			
FAR Part 36	7735 (4176)*	8705 (4700)	7535 (4068)

*Includes advanced takeoff procedures

3.2 TECHNOLOGY SENSITIVITY STUDY

A technology sensitivity study of the VSCE and rear-valve VCE was made with two approaches to different technologies. Since in Phase III the VSCE had been identified as the most promising VCE concept, the technology sensitivity study concentrated on this engine. The rear-valve VCE was included in these sensitivity studies to determine if nearer term technology would affect the potential of this engine relative to the VSCE. The first approach to technology sensitivity was to evaluate the impact of nearer term technology on engine performance and vehicle range. This approach reoptimized the VSCE and rear-valve VCE for the nearer term technology. The second approach was to study the effect of missing some of the far term technology goals during the development program and to determine the impact that this missed goal would have on engine performance and airplane range.

As a result of these studies, the VSCE concept was shown to be capable of being redefined for nearer term technology without significant compromises to airplane performance characteristics. Table 3-II compares the cycle and airplane range of the nearer term technology VSCE-511 to the far term VSCE-502B. The effect of nearer term technology on the rear-valve VCE resulted in about the same overall impact as it did on the VSCE. Figure 3-2 compares the range of the VSCE and rear-valve VCE for both technology levels. Based on these results, it was concluded that the rear-valve VCE, since it did not perform as well as the VSCE at either technology level and is a more complicated concept, was of no further interest. Therefore, work was discontinued on the rear-valve VCE concept.

TABLE 3-II
VSCE TECHNOLOGY SENSITIVITY STUDY

	VSCE-502B	VSCE-511
Technology readiness	Late 1980s (Far term)	Early to mid 1980s (Nearer term)
Cycle		
Fan pressure ratio	3.3	3.3
Overall pressure ratio	20	13.4
Bypass ratio	1.3	0.85
Max. combustor exit temp — °C (°F)	1480 (2700)	1370 (2500)
Engine + N/R weight — kg (lbm)*	6080 (13,400)	6085 (15,400)(+ 15%)
Engine + N/R length — m (in.)*	6.76 (266)	7.26 (286)(+ 7.6%)
Range km (n. mi.)		
FAR Part 36	8890 (4800)	7965 (4300)(-10%)
FAR Part 36 —5dB	7935 (4300)	7040 (3800)(-12%)

*408 kg/sec (900 lbm/sec) airflow size

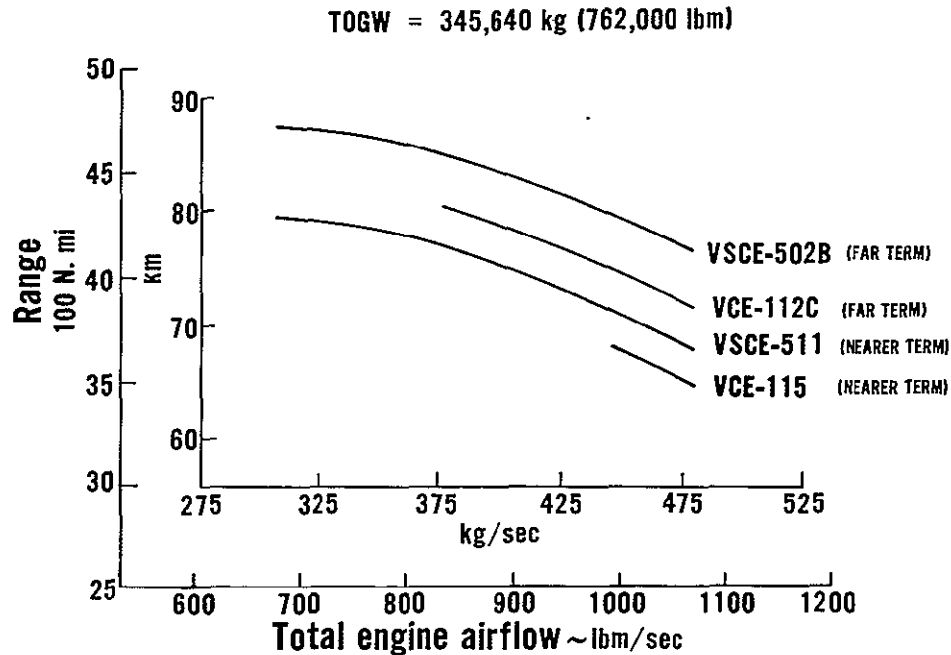


Figure 3-2 Comparison of Range With Variable Stream Control Engine and Rear-Valve Variable Cycle Engine Concepts For Both Far-Term and Nearer Term Technology Levels

The effect of missing a projected development goal in several critical areas of technology was evaluated in the VSCE-502B. Table 3-III shows the vehicle Δ range for the VSCE-502B for each of the technology deficits evaluated. These results show that exhaust nozzle performance and coannular noise benefit have a very significant effect on airplane range. Although not as sensitive in affecting airplane range, turbine efficiency and cooling technology and duct burner efficiency are very critical in establishing an economically attractive VSCE. Turbine technology is required to provide the VSCE cycle features, especially the 1.3 BPR, which is required for good performance and for the coannular noise benefit. High duct burner efficiency is needed to reduce emissions and for low fuel consumption in supersonic cruise.

TABLE 3-III

TECHNOLOGY SENSITIVITY FACTORS

Technology deficit	Δ Range — km (n. mi.)
—1 point in C_v	— 352 (—190)
—2 dB in coannular noise benefit	— 204 (—110)
+ 2 points in turbine cooling air }	
—0.5 point in turbine efficiency }	— 74 (—40)
—1 point in duct burner efficiency	— 37 (—20)
+ 2% in engine + N/R weight	— 37 (—20)

3.3 PROGRAM RECOMMENDATIONS

Advanced technology programs are required to substantiate technology readiness for the VSCE. Critical technology requirements for the VSCE concept are as follows:

- Low noise, high performance coannular nozzle,
- Low emissions, high performance duct burner,
- Variable geometry components,
- Low emissions, high performance main burner,
- Hot section technology,
- Full authority electronic control system, and
- Propulsion system integration.

A study effort focusing on the areas of engine/airframe integration and VSCE design refinement is recommended. Recommendations for joint engine/airplane company integration studies are shown in Table 3-IV. VSCE design refinement should include:

- Preliminary design of the VSCE,
- Preliminary design of the integrated VSCE propulsion system.

Program recommendations related to the critical technology requirements and suggested programs for the study efforts are described in Section 5.0.

TABLE 3-IV

RECOMMENDATIONS – JOINT ENGINE/AIRPLANE COMPANY INTEGRATION STUDIES

Preliminary design of nozzle/reverser

- Aero/acoustic configuration
- Reverser targeting and effectiveness
- Trade studies
- Mechanical
- Structural
- Acoustic treatment

Preliminary design of engine/airframe interface systems

- Secondary flow system
- Fuel/air/oil thermal management
- Airframe accessories
- Integrated control system

Continue evaluation of programmed throttle schedule, for noise abatement

Preliminary design of inlet/engine

- Variable geometry requirements
- Performance
- BLC system
- Structural
- Mechanical
- Stability/distortion
- Noise control

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4.0 RESULTS AND DISCUSSION

The results of the Phase IV study are presented in three sections. First, the VSCE cycle selected for study by each airframe contractor is described, in respect to cycle airflow scheduling and installation characteristics, as well as noise and emissions estimates. Next, the results of each airframe contractor study are presented and discussed. Finally, the impact of technology on selected engines is presented, including the impact of nearer term technology, and an evaluation of the sensitivity of each engine cycle to variations in technology level (for example, failure to meet far term technology goals).

4.1 ENGINE/AIRFRAME INTEGRATION STUDY

During the Phase III study, P&WA provided the SCAR airframe contractors with engine data packs for the most promising concepts. Based on the airframe contractors installed evaluation of these concepts and the results of their airplane/propulsion system studies, each contractor identified the advanced VSCE as the engine concept that has the potential to provide the best balance of supersonic and subsonic performance, and to meet environmental requirements projected for future supersonic aircraft. The VSCE was therefore selected as the engine concept to be evaluated during the Phase IV integration studies.

4.1.1 VSCE Description

The VSCE is an advanced duct burning turbofan concept that makes extensive use of variable geometry components. It features a flexible throttle schedule allowing independent variation of the two coannular exhaust streams. This unique scheduling capability provides the inverse velocity profile (bypass stream velocity greater than primary stream velocity) needed to take advantage of the inherent jet noise benefit of the coannular nozzle at take-off, while at subsonic and supersonic conditions, the exhaust velocities can be matched to provide a flat profile for high propulsive efficiencies. Figure 4.1-1 shows the basic arrangement of the major engine components. It is a twin spool configuration similar to a conventional turbofan. The low spool consists of an advanced technology, multi-stage, variable geometry fan and a low pressure turbine. The high spool consists of a variable geometry compressor driven by an advanced single stage high temperature turbine. The primary burner is a low-emissions, high efficiency combustor concept such as the two stage vorbix design evaluated in the NASA/P&WA Experimental Clean Combustor Program. A preliminary definition of the duct-burner has evolved from a NASA/P&WA low emissions duct-burner screening program, NAS3-19781. The present configuration is a three zone burner utilizing many of the same mixing concepts which comprise the vorbix main burner. The nozzle is a two stream concentric, annular (coannular) design with variable throat areas in both the primary and bypass streams, and includes an ejector/reverser system. The VSCE cross-section shown in Figure 4.1-1 differs from the Phase III definition in two areas: it has the 3 zone vorbix duct burner design selected for experimental evaluation (Section 5.2) and it has a simplified coannular nozzle design.

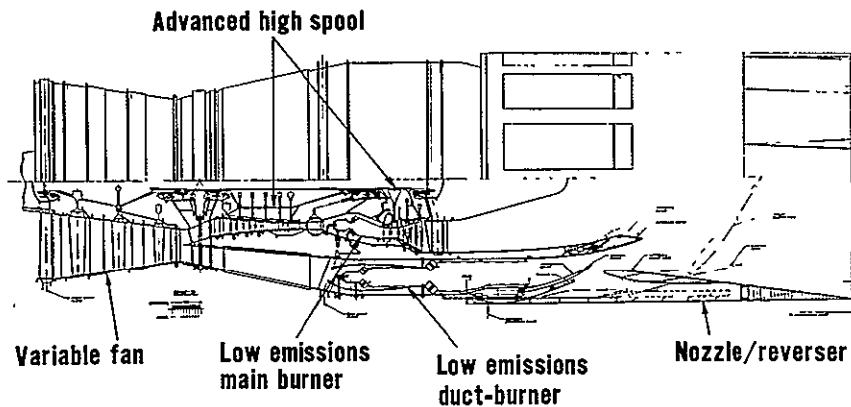


Figure 4.1-1 Variable Stream Control Engine VSCE-502B

4.1.2 Engine Cycle and Installation Descriptions

Three SCAR airframe contractors have been conducting configuration studies with the objective of defining the advanced technology requirements and design features necessary for an economically viable advanced supersonic cruise airplane. Different design philosophies and analytical techniques have resulted in configurations which require different propulsion system packages. This section includes a brief discussion of the selected VSCE cycle, airflow schedules and installation characteristics used by each airframe contractor. Noise and emissions estimates for the VSCE are also discussed.

4.1.2.1 Boeing Propulsion System

Base Cycle

The VSCE cycle selected by Boeing is identified as the VSCE-502B. This engine has been refined for Mach number 2.4 cruise which matches the Boeing baseline aircraft requirements and has the flexibility to be scaled to match variations in airplane size. The cycle characteristics, weight and dimensions are summarized in Table 4.1-I.

Airflow Schedule

Inlet/engine airflow matching has received closer attention as the requirements of advanced aircraft have demanded a fine tuning of the aircraft and engine interfaces to operate at optimum performance levels over a broad flight envelope. The VSCE, because of its unique throttle schedule and variable geometry components, is capable of accepting a wide range of inlet conditions which allows a reduction of inlet drag levels due to spillage and bypass losses. The original VSCE-502B utilized a representative supersonic inlet flow characteristic carried over from general parametric engine studies. Subsequent to this definition, an airflow schedule which more closely matches the requirements of Boeings installation was provided by Boeing and applied to the VSCE-502B. This airflow schedule and an approximation of the VSCE-502B scheduling flexibility is illustrated in Figure 4.1-2.

TABLE 4.1-I

BASE CYCLE FOR BOEING STUDIES
(VSCE-502B)

Technology Readiness	Late 1980's
Cruise Mach Number	2.32
Takeoff Airflow Size ~ kg/sec (lbm/sec)	320 (700)
Cycle	
Fan Pressure Ratio	3.3
Bypass Ratio	1.3
Overall Pressure Ratio	20:1
Maximum Combustor Exit Temperature ~ °C (°F)	
Primary Burner	1480 (2700)
Duct Burner	1430 (2600)
Engine Weight ~ kg (lbm)	4630 (10,200)
Maximum Diameter ~ m (in)	2.00 (78.8)
Overall Length ~ m (in)	5.95 (235)

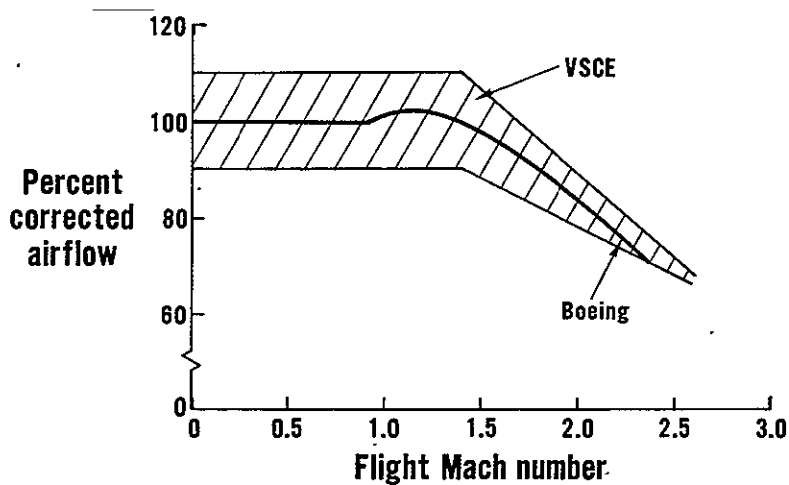
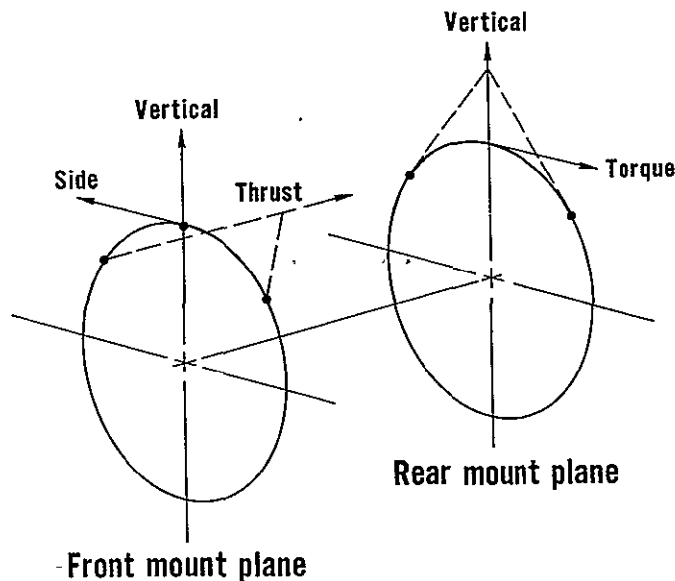


Figure 4.1-2 Boeing Airflow Schedule

Engine/Airframe Installation

Figure 4.1-3 is a schematic illustration of a conventional mount concept capable of providing the support required for the VSCE in the Boeing installation. This isometric drawing shows the load vectors acting on the engine at the front and rear mount planes. For the arrangement shown, the inlet and nozzle/reverser systems are engine supported. Structural nacelle concepts are being evaluated which tie the inlet directly to the wing permitting removal of the engine independent of the inlet. A review of the potential engine or airplane benefits will provide the basis for selection of an optimum nacelle concept and mount configuration.



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Figure 4.1-3 Boeing Engine Support Concept

General accessory requirements for the VSCE-502B were determined for the Boeing installation. The sizes and locations of the engine mounted accessories are shown in the installation drawing of Figure 4.1-4. Aircraft accessories are wing mounted to reduce packaging complexity and avoid impacting the engine nacelle contour. These remote accessories, including the starter, generator and hydraulic pumps, are driven through a power takeoff directed from the engine to the aircraft gearbox.

The VSCE-502B nozzle/reverser is of the auxiliary inlet ejector type, a design which provides high performance levels by allowing controlled variations in the jet area of both streams while limiting the overall expansion of the exhaust with self-adjusting nozzle exit flaps. The auxiliary inlet doors are easily programmed to satisfy the ejector mode and targeted flow for the reverse mode. An optimum cruise thrust nozzle configuration is obtained by aligning the nozzle centerline with the wing reference plane. An angle of 3.5 degrees between the engine and nozzle centerlines achieves the desired result.

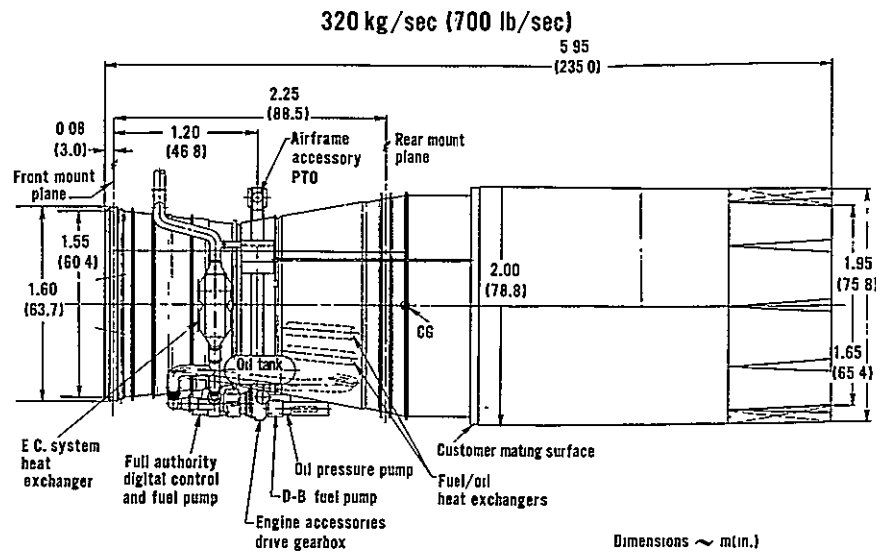


Figure 4.1-4 Boeing Installation Drawing, VSCE-502B

4.1.2.2 Douglas Propulsion System

Base Cycle

The Douglas baseline aircraft is designed for Mach number 2.2 cruise. The engine cycle selected for the Douglas studies is the VSCE-502BD. This cycle was designed for Mach 2.2 cruise and sized for the requirements of the Douglas Aircraft. Table 4.1-II lists the cycle and installation characteristics of the VSCE-502BD.

Airflow Schedule

Inlet airflow and pressure recovery characteristics have a significant effect on engine performance. Design studies are continuing at Douglas to achieve an optimum inlet/engine match through various airflow and throttle scheduling techniques. Recent definition of a mixed compression inlet by Douglas has resulted in the airflow schedule illustrated in Figure 4.1-5.

Engine/Airframe Installation

The proposed load removal concept for the VSCE consists of front and rear mount rings located over the fan inlet guide vane and duct burner inlet, respectively. Discrete mount points are located in the upper portion of the mount ring flanges and transfer all engine loads to the airplane structure. The nozzle loads are transferred directly to the engine, and two methods have been investigated for supporting the engine inlet.

TABLE 4.1-II

BASE CYCLE FOR DOUGLAS STUDIES
(VSCE-502BD)

Technology Readiness	Late 1980's
Cruise Mach Number	2.2
Takeoff Airflow Size ~ kg/sec (lbm/sec)	342 (754)
Cycle	
Fan Pressure Ratio	3.3
Bypass Ratio	1.3
Overall Pressure Ratio	20:1
Maximum Combustor Exit Temperature ~ °C (°F)	
Primary Burner	1480 (2700)
Duct Burner	1430 (2600)
Engine Weight ~ kg (lbm)	5030 (11,100)
Maximum Diameter ~ m (in)	2.05 (80.5)
Overall Length ~ m (in)	6.25 (246)

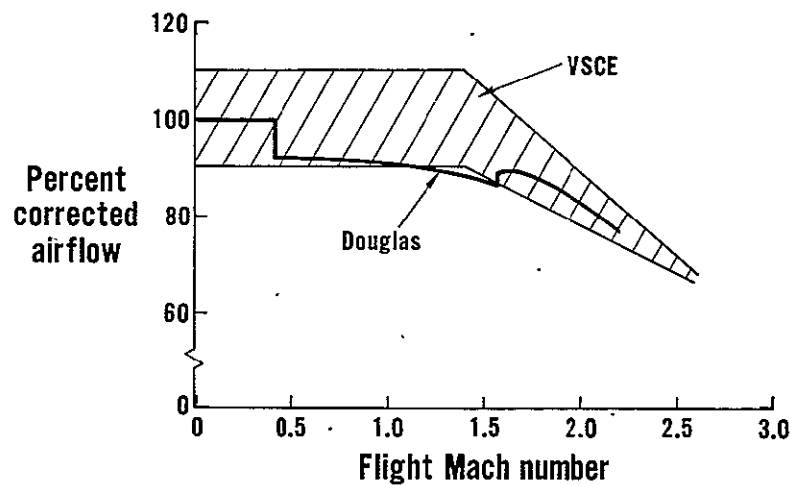


Figure 4.1-5 Douglas Airflow Schedule

Both a structural nacelle concept and a non-structural arrangement have been defined for application to the VSCE-502BD. The structural nacelle package is somewhat lighter because the inlet is not engine supported, but attaches directly to wing structure through the pylon and upper cowl. With this arrangement, a flexible seal is required between the inlet and engine to permit relative motion and avoid increased stresses. The non-structural nacelle assumes the inlet to be engine supported which eliminates the requirement for the seal, but requires a nominal engine weight increase to account for the higher mount and case loads. The rigid connection between engine and inlet provides a smooth continuous flowpath with no steps or gaps to cause flow discontinuities at the fan tip.

Neither of the nacelle concepts has a major impact on the engine. Figure 4.1-6 is a load removal schematic which satisfies the requirements of either concept. Engine and airframe accessories are not affected by the nacelle scheme; airframe accessories are wing mounted for better engine accessibility and engine accessories are distributed on the engine case in such a way that nacelle contours are undisturbed and core access is allowed. The engine installation sketch in Figure 4.1-7 shows the overall arrangement of the 502BD dressed for the Douglas installation. A tower shaft at the 12 o'clock position provides power for fuel related accessories and the wing mounted aircraft gearbox. At the bottom of the engine, a second tower shaft drives an auxiliary gearbox and the oil scavenge system pump.

The performance of the VSCE nozzle exerts a large influence on the overall propulsion system. The baseline definition has both variable primary and duct stream areas leading into a common auxiliary inlet ejector nozzle with self-actuated flaps to provide smooth controlled expansion of the two exhaust streams. Circumferentially located panels are actuated during low Mach number operation for the ejector airflow. Reverse thrust is accomplished by deploying two blocker doors and selectively opening the auxiliary inlet panels to supply the targeting required for each engine location.

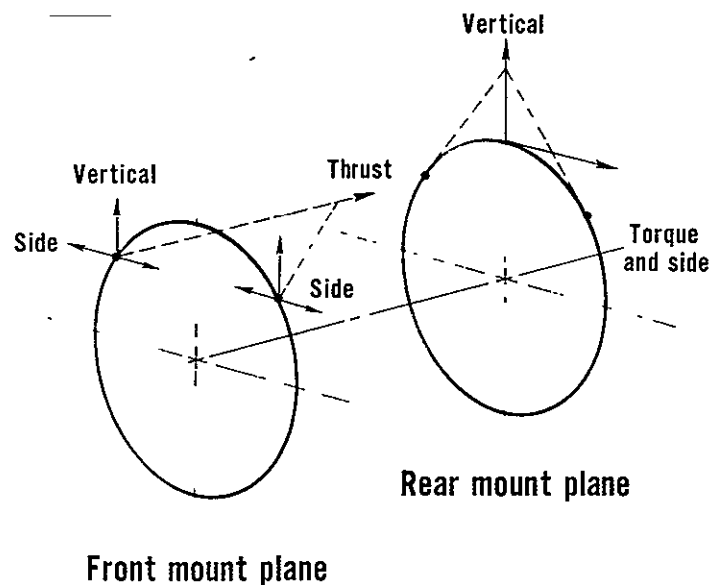


Figure 4.1-6 Douglas Engine Support Concept

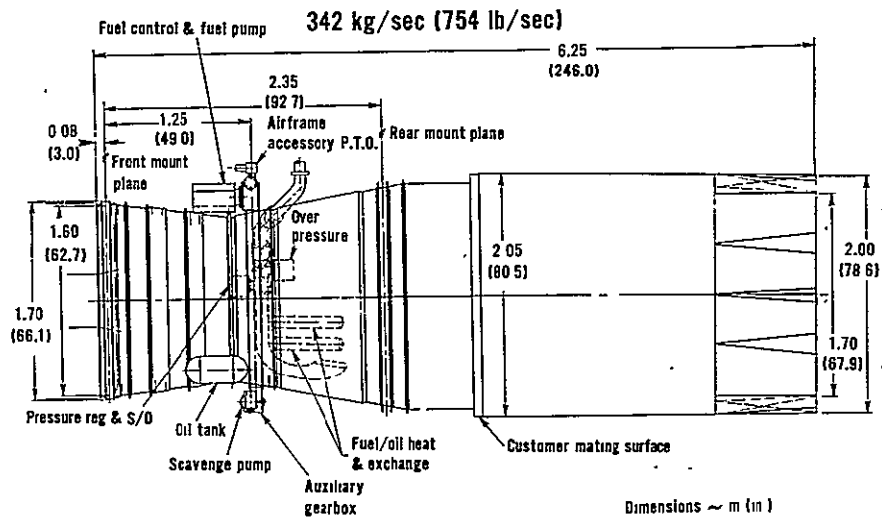


Figure 4.1-7 Douglas Installation Drawing, VSCE-502BD

4.1.2.3 Lockheed Propulsion System

Base Cycle

The VSCE-516 was selected as the base cycle for the Lockheed engine/airframe integration studies. Designed for Mach 2.6 operation, the VSCE-516 matches the Mach number and thrust requirements of Lockheed's baseline study aircraft. A summary of the engine cycle, weight, and dimension characteristics is listed in Table 4.1-III.

Airflow Schedule

The engine airflow schedule used in defining propulsion system performance levels for Lockheed is shown in Figure 4.1-8. This airflow characteristic is supplied by the axisymmetric inlet defined by Lockheed for their Mach 2.62 aircraft. Included in this airflow schedule is a high flow capability, within the limits of inlet and engine, to improve the operating characteristics of the VSCE-516 over a range of transonic Mach numbers.

Engine/Airframe Installation

Lockheed's configuration studies have shown an over/under engine location arrangement to be an attractive alternative to a conventional four engine under-wing arrangement. The impacts of this system on the engine installation are restricted to certain of the fuel, oil and accessory requirements; other engine components remain unchanged.

The Lockheed engine mount arrangement provides for separate pickup of the inlet and engine loads with a flexible seal joining the two. This seal restricts any leakage at the engine/inlet interface but permits free relative movement. Engine support is by two ball joints at the engine front mount which allows enough freedom of movement to permit unrestricted thermal expansion. These forward locations accept thrust, side, and vertical loads while at the rear mount ring two vertical swivel links support vertical loads only. A schematic representation of this engine mount arrangement is shown in Figure 4.1-9 for the lower engine. A mirror image schematic would represent the support arrangement for the upper engine.

TABLE 4.1-III

BASE CYCLE FOR LOCKHEED STUDIES
(VSCE-516)

Technology Readiness	Late 1980's
Cruise Mach Number	2.55
Takeoff Airflow Size ~ kg/sec (lbm/sec)	272 (600)
Cycle	
Fan Pressure Ratio	3.3
Bypass Ratio	1.3
Overall Pressure Ratio	16:1
Maximum Combustor Exit Temperature ~ °C (°F)	
Primary Burner	1480 (2700)
Duct Burner	1430 (2600)
Engine Weight ~ kg (lbm)	3990 (8800)
Maximum Diameter ~ m (in)	1.80 (71.5)
Overall Length ~ m (in)	5.60 (220)

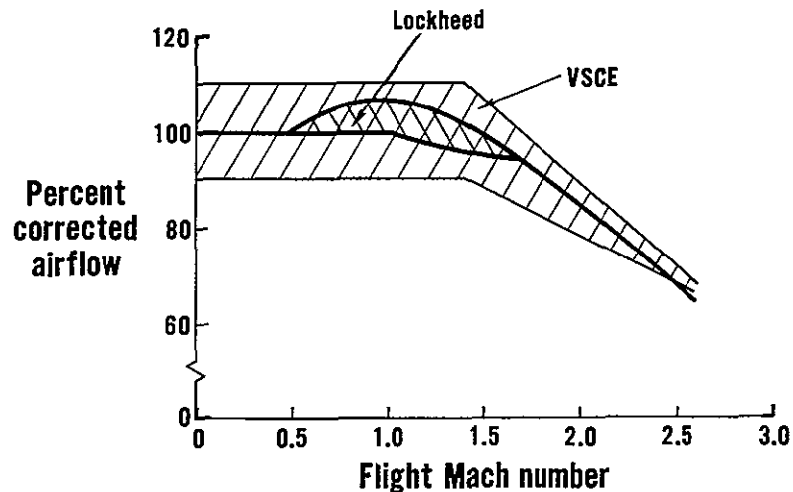


Figure 4.1-8 Lockheed Airflow Schedule

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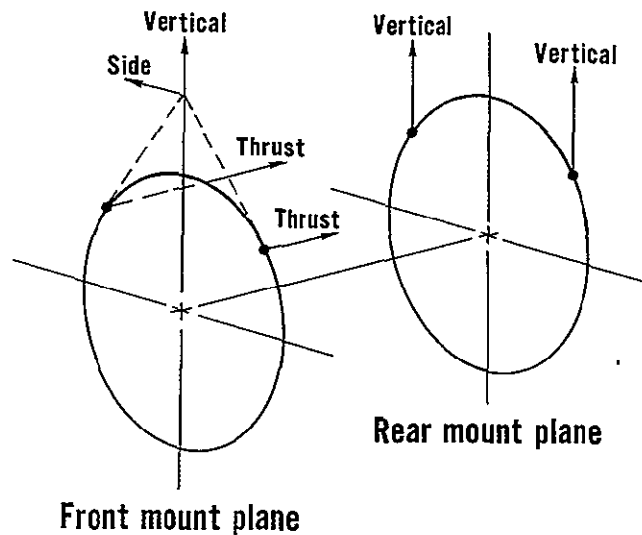


Figure 4.1-9 Lockheed Engine Support Concept

All propulsion system accessories are located to minimize the impact to the nacelle contours. This is accomplished by locating the larger engine and airframe accessories in the wing pylon, and the remainder of the engine accessories on the outer engine case, in the region of reduced diameter. Because certain of the lubrication and fuel systems depend on gravity for proper operation, the over/under arrangement causes some minor problems. In either the upper or lower engine location, the oil scavenge pump, filter, tank, and lines must be mounted on the lower side of the engine to maintain the proper bearing compartment lubrication. All other fuel or accessory lubrication systems must be located in such a way that vent and drain lines are properly oriented. Several methods of providing a common engine for both upper and lower installations are being explored and each requires a certain amount of redundancy or repositioning of accessories for proper orientation. Figure 4.1-10 illustrates the installed outline for the VSCE-516 showing the accessory arrangement characteristic of the lower pod. An aerodynamic cowl is used to cover the engine accessories located in the region between the engine front and rear mounts. Aft of the rear mount, a short section of structural cowl is employed to support a beam running parallel to the centerline of the engine which supports the aerodynamic cowl when pod access is required.

Design input from both Lockheed and P&WA was used in determining VSCE-516 engine size, aircraft accessory sizes and positioning for easy access, the engine support arrangement and the nozzle/reverser system. A parametric nozzle/reverser/ejector configuration was initially included in the VSCE-516 which has since been updated to reflect a simplification of the nozzle mechanical arrangement. The modified design designated VSCE-516L (Figure 4.1-11) resulted in an overall engine length increase due to eliminating a set of hinged flaps in the ejector door system and changing to a long flap iris nozzle for controlling the nozzle throat area in the bypass stream. Several nozzle configurations have been defined which satisfy the requirements of this engine and, because the performance of each is essentially equal, the trade involves weight and mechanical simplicity. Further design studies, which will draw input from the aero/acoustic nozzle test program presently being conducted by P&WA under NASA contract, are necessary to determine the optimum balance of weight, performance, price, and complexity.

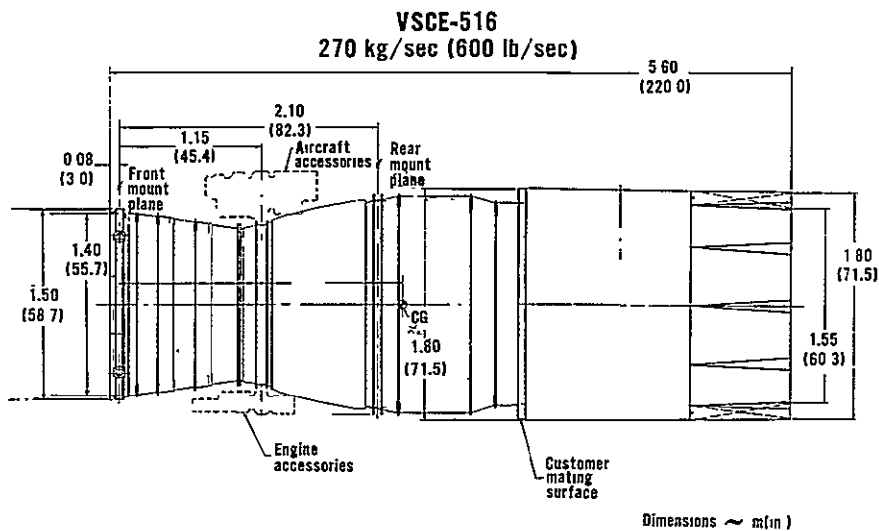


Figure 4.1-10 Lockheed Installation Drawing, VSCE-516

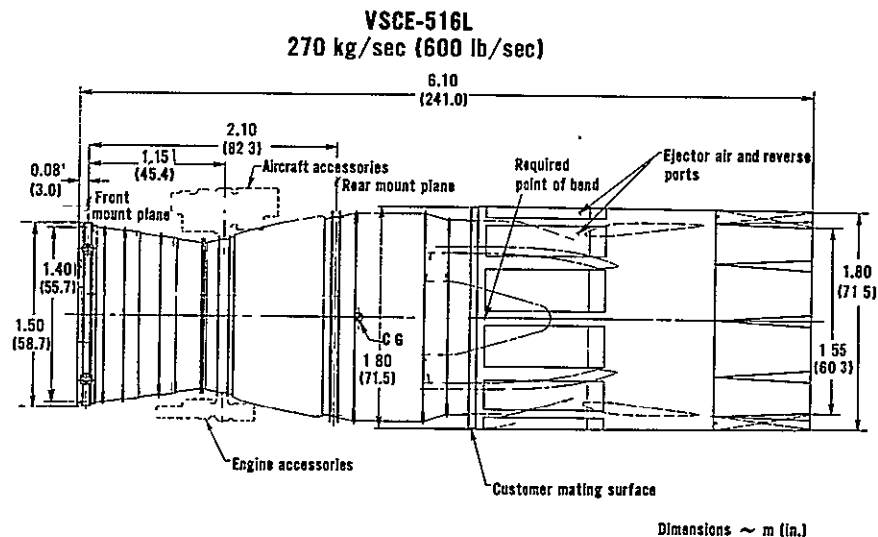


Figure 4.1-11 Lockheed Installation Drawing, VSCE-516L

An analysis of the engine/aircraft interface has indicated that having the engine exhaust streams directed to an angle approximately $2\frac{1}{2}$ degrees below the horizontal reference plane provides a favorable lift vector without affecting the optimum thrust line and flight path at cruise. This requirement does not complicate the nozzle design and is accomplished for both the upper and lower installations with an interchangeable nozzle.

4.1.3 Noise Estimates

The VSCE employs extensive variable geometry and unique throttle scheduling to achieve low jet noise at take-off while maintaining high performance at subsonic and supersonic cruise conditions. Jet noise is the prime contributor to total engine noise at take-off. This noise component is reduced by the coannular nozzle benefit which results from the inverted velocity profile of the coannular exhaust streams. The inverted velocity profile, illustrated in Figure 4.1-12, is attained by independent control of the two exhaust streams in combination with cycle features of the VSCE concept. Static and simulated forward speed model nozzle testing under NASA Contract NAS3-17866 has experimentally demonstrated the coannular nozzle noise benefit (Section 5.1).

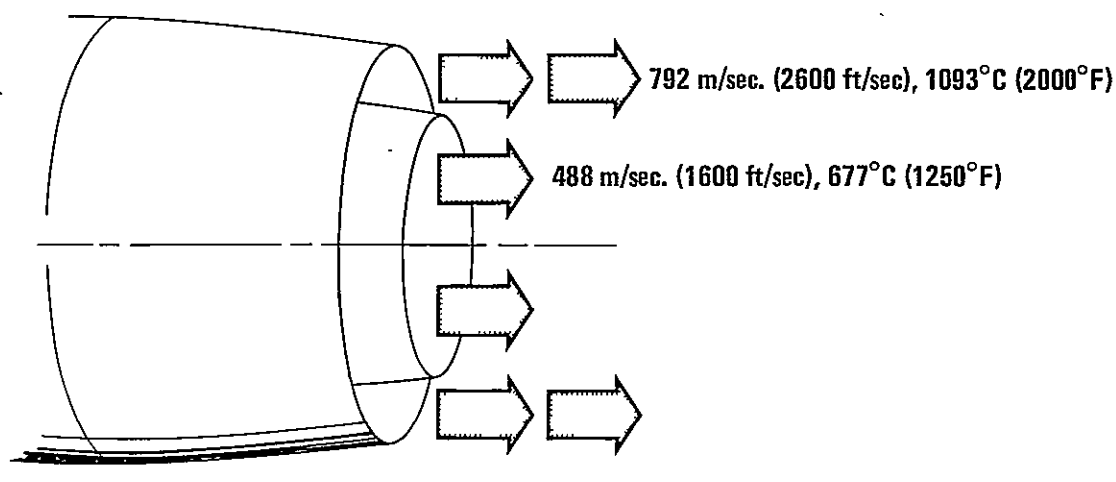


Figure 4.1-12 Coannular Nozzle Velocity Profile Required for Low Noise

Acoustic studies have shown that rematching the engine and using the variable geometry of the VSCE fan to alter the fan pressure ratio at take-off can result in further noise level reductions. To optimize the coannular benefit for the VSCE, a study was conducted to examine parametrically the effects of throttle scheduling and fan matching on take-off noise. The ground rules for this study are shown in Table 4.1-IV.

A range of fan pressure ratios and duct-to-engine stream velocity ratios that are within the capability of the VSCE was examined. Simulated engine performance characteristics at each of the study matrix points were used to estimate total engine noise values, including the coannular reduction effect. The results of this noise analysis are presented in Figure 4.1-13. As shown, for a constant level of thrust, take-off noise decreases gradually with increasing jet velocity ratio and the noise level drops significantly (1.7 dB) when the fan pressure ratio is reduced. A constraint not indicated on the plot is a duct burner exit temperature limit of 1430°C (2600°F) set by liner material and cooling flow capabilities. Imposing this temperature limit restricts the optimum coannular noise reduction benefit to a jet velocity ratio around 1.7 at the lower fan pressure ratio. Further studies of the VSCE take-off cycle characteristics, especially programmed throttle scheduling, will concentrate on this range of coannular exhaust conditions.

TABLE 4.1-IV

VSCE TAKE-OFF STUDY GROUND RULES FOR OPTIMIZING
COANNULAR NOISE BENEFITS

Constants

- Sea level, 0.3 Mn, Std. + 10°C (18°F)
- 215,700 N (48,500 lbf) net thrust
- 340 kg/sec (750 lbfm/sec) corrected airflow

Variables

- 2.8, 3.3 FPR
- 1.6, 1.7, 1.8 V_{jd}/V_{je}

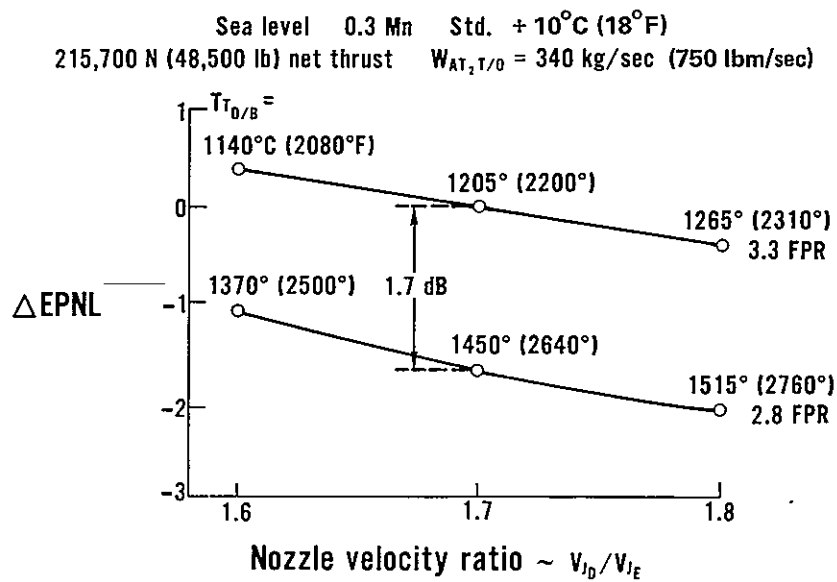


Figure 4.1-13 VSCE Noise Characteristics

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4.1.4 Emissions Estimates

Emissions data from the NASA/P&WA Experimental Clean Combustion Program (ECCP) have been used to update the emissions estimates for the VSCE concept. Configuration changes to the VSCE-502B duct burner based on the Duct Burner Analytical Screening Program (Section 5.7) provide a refined definition for the duct burner emissions. These refinements are reflected in the emissions indices (EI) summarized in Figure 4.1-14. The five flight conditions represent those which contribute to the airport operating environment emissions parameter. In addition to the EI's, the relative contribution of each flight condition to the EPA emissions parameter for the carbon monoxide (CO) and nitrous oxide (NO_x) emissions are shown in Figure 4.1-14. As indicated, taxiing operation contributes the most NO_x , while take-off operation produces the greatest CO. The actual EPA Parameters (EPAPs) for the VSCE-502B for CO, NO_x , and unburned hydrocarbons (THC) are shown in Figure 4.1-15 with the EPA Class T5 rule for supersonic transports superimposed. For each of the three pollutants, a lower EPAP level is indicated representing an ideal condition where no duct burner emissions are present. This level illustrates the main burner is the dominant source of NO_x and two thirds of the CO is from the duct burner. THC levels are close to the EPA rule. Test data from the duct burner programs described in Section 5.2 will provide reliable information to update these estimates.

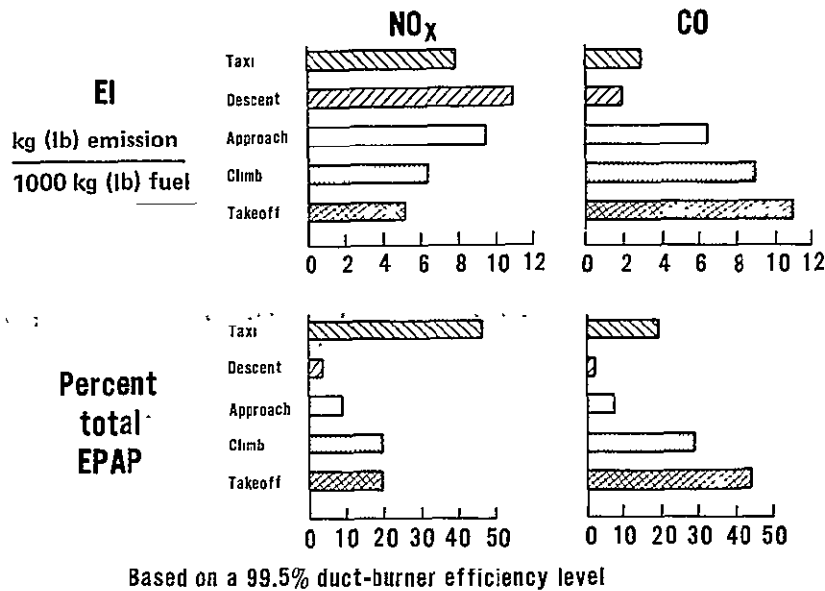


Figure 4.1-14 VSCE-502B Emissions Estimates

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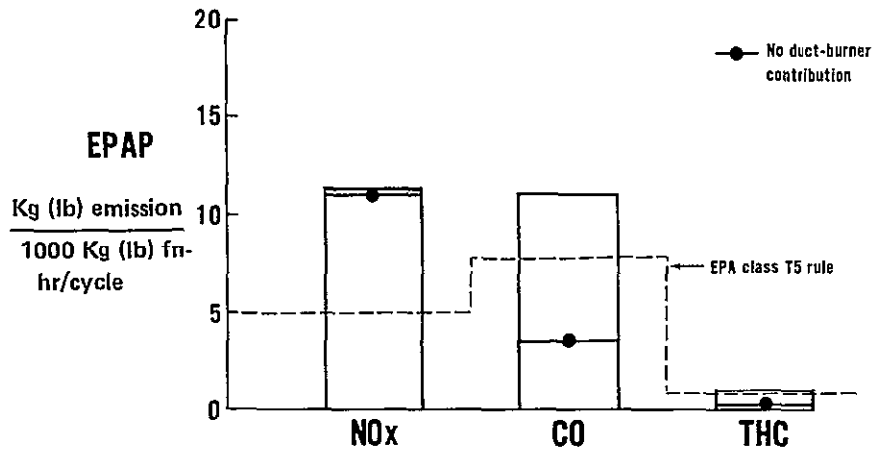


Figure 4.1-15 VSCE-502B EPAP Estimates Compared to EPA Requirements

4.2 SUMMARY OF AIRPLANE COMPANY STUDY RESULTS

The three SCAR contractors, Boeing, Douglas and Lockheed, conducted engine/airplane integration studies as part of Phase IV under subcontract to P&WA. The significant conclusions of the airplane companies are presented in Tables 4.2-1 through 4.2-III. The Boeing study results are summarized in Section 4.2.1, Douglas in 4.2.2 and Lockheed in 4.2.3.

TABLE 4.2-I

SIGNIFICANT CONCLUSIONS FROM THE BOEING INTEGRATION STUDY

- The near term engine, which is the 1985 technology VSCE-511, has 560 km (300 n. mi.) less peak range relative to the -502B. This range increment is indicative of the impact of a 5 year difference in engine design technology, and is primarily related to the core engine hot end operating temperatures and cooling efficiencies. It is recommended that development effort be emphasized on the technology for higher operating temperature and greater cooling efficiencies.
- The results of the near term rear-valve VCE performance study indicate the VCE performance degenerated as much or slightly more than the VSCE engine. It is concluded, on the basis of these findings and the indication of a higher jet noise for the VCE cycle, that further development of the rear-valve VCE cycle is not warranted for this particular design speed and application.
- The nozzle thrust coefficient at supersonic cruise condition impacts a dominant sensitivity on overall engine performance.
- The VSCE-502B maximum airflow demand is well matched to the inlet characteristics over the entire Mach number range.

TABLE 4.2-II

SIGNIFICANT CONCLUSIONS FROM THE DOUGLAS INTEGRATION STUDY

- The study revealed, to the depth accomplished, that the P&WA VSCE 502B installed on the 2.2M MDC baseline supersonic cruise transport is a viable candidate engine. This engine results in a 5.3% longer range than the P&WA rear-valve VCE-112C installed on the aircraft.
- The structural nacelle - engine inlet supported directly by the wing rather than from the engine front flange - results in a 41 kg (91 lb.) weight saving per pod over the non-structural nacelle. The engine can be removed without removing the inlet.
- Engine and airplane accessories package efficiently and permit easy access for inspection and removal.
- Technology assessment and airplane sensitivity studies show that the airplane range is most sensitive to noise and nozzle performance.
- Further refinements of the VSCE 502B engine cycle should be investigated in order to maximize the range utilizing the MDC 2.2H baseline supersonic cruise transport.
- Nacelle design should be accomplished in greater depth to further reduce weight. Improve access and optimize nacelle location to minimize installation penalties.
- Further critical engine technology projections in greater depth should be accomplished to better define engine performance level as a function of engine development start date.
- Areas of future effort based on technology assessments are noise suppression, exhaust nozzle performance, engine weight, and turbine cooling air.

TABLE 4.2-III

SIGNIFICANT CONCLUSIONS FROM THE LOCKHEED INTEGRATION STUDY

- Satisfactory design integration (on a preliminary design basis) of the VSCE-516 engine has been achieved with the over/under nacelle concept as defined for the CL1607 aircraft. Continued design study is needed to minimize the installation differences between over-wing and under-wing nacelles. In the long run, the additional design requirements must be traded-off against the identified over/under advantages, to determine optimal engine location.
- Continued development toward reduced size in engine and airframe accessories is necessary to provide satisfactory accessory installation, as well as to prevent range or weight degradation due to nacelle drag.
- The maximum commonality inlet concept deserves further study, because this configuration not only reduces production complexity, but also reduces airline inventory requirements.
- The capability of the full-authority digital control has been assumed to provide inlet/ airflow matching. Additional study should be initiated to investigate the engine-airframe control integration that is necessary to take maximum advantage of the control capability.

- Three possible engine configurations have been identified which provide for over/under engine installation of identical engines. The first arrangement uses gearbox and engine sumps that allow the engine to be inverted. The second provides power offtakes top and bottom which can drive either gearbox. The third provides a single, centrally located power offtake, to drive remotely located accessories.
- Additional noise tests and analyses are required to establish the level of jet noise shielding which is obtained by virtue of the over/under arrangement. More detailed analyses should be conducted to determine the effect of fan noise transmitted through the inlet auxiliary doors and, if necessary, devise noise reduction techniques that will be effective in reducing fan noise to acceptable levels.
- Based upon the results of the technology sensitivity study conducted for the VSCE-516, it appears that the primary research emphasis should be in the areas of coannular noise relief demonstration, nozzle performance verification, and turbine cooling technology. In addition, because of environmental concerns, efforts must also be directed toward a clean, efficient duct burner.

4.2.1 Boeing Integration Study

In addition to improving the installed performance of the integrated VSCE propulsion system (Section 4.1.2.1), the Boeing study evaluated the range impact of nearer term technology versions of the VSCE-502B and rear-valve VCE-112C engines. Other objectives included evaluation of VSCE-502B component sensitivity factors, investigation of the effect of duct burner cooling flows on coannular noise reduction, and comparison of engine airflow demand with a revised inlet flow schedule.

4.2.1.1 Evaluation of Nearer Term VSCE

Cycle characteristics of the three VSCE engines considered in the evaluation are shown in Table 4.2-IV, including the VSCE-510 for which preliminary data were provided. The VSCE-511 superseded the VSCE-510 as a refined version of the nearer term technology engine. Installed VSCE-502B and VSCE-511 supersonic and subsonic cruise performance is shown in Figure 4.2-1 for 320 kg/sec (700 lb/sec) engine size.

Mission performance of these engines was evaluated on the blended wing/body airframe Model 733-630. This airplane is designed for long range supersonic cruise at a nominal speed of Mach number 2.4 and a maximum gross weight of 340,190 kg (750,000 lb). Engine installations of the study airplane were defined and evaluated for different candidate engines. The wing was optimized for the VSCE-502B sized for 320 kg/sec (700 lb/sec) airflow.

This evaluation was conducted with fixed values for maximum take-off gross weight (340,190 kg (750,000 lb)), wing area 715 m^2 (7700 ft^2), payload (273 passengers) and operating empty weight minus propulsion pod weight (123,340 kg (271,920 lb)) for a standard +8°C (14.4°F) day. Nacelle drag was held constant for the engines in this analysis; total airplane drag was not varied with engine size since this effect had been assessed as small. A pod weight breakdown is shown below for 408 kg/sec (900 lb/sec) size engines.

TABLE 4.2-IV

CYCLE CHARACTERISTICS
SEA LEVEL STATIC, STANDARD DAY, AERO DESIGN POINT

Engine	VSCE-502B	VSCE-511	VSCE-510
Time Frame			
— Technology Readiness	Late 80's	Early 80's	
— Certification	Mid 90's	Late 80's	
Inlet Corrected Airflow (W_{AT2}) ~ kg/sec (lb/sec)	408 (900)	408 (900)	408 (900)
Overall Pressure Ratio (OPR)	20:1	13.6:1	13.4:1
Bypass Ratio (BPR)	1.3	0.85	0.77
Fan Pressure Ratio (FPR)	3.3	3.3	3.3
Maximum Combustor Exit Temp. (CET) ~ (°C) (°F)	1480 (2700)	1370 (2500)	1370 (2500)
Maximum Compressor Discharge Temperature (CDT) ~ (°C) (°F)	700 (1300)	620 (1150)	620 (1150)
Turbine Cooling Air (TCA) % Engine Airflow	10.7	15.0	18.0
Relative Duct Burner Thrust Effective Efficiency	—	-2.5%	-4.5%

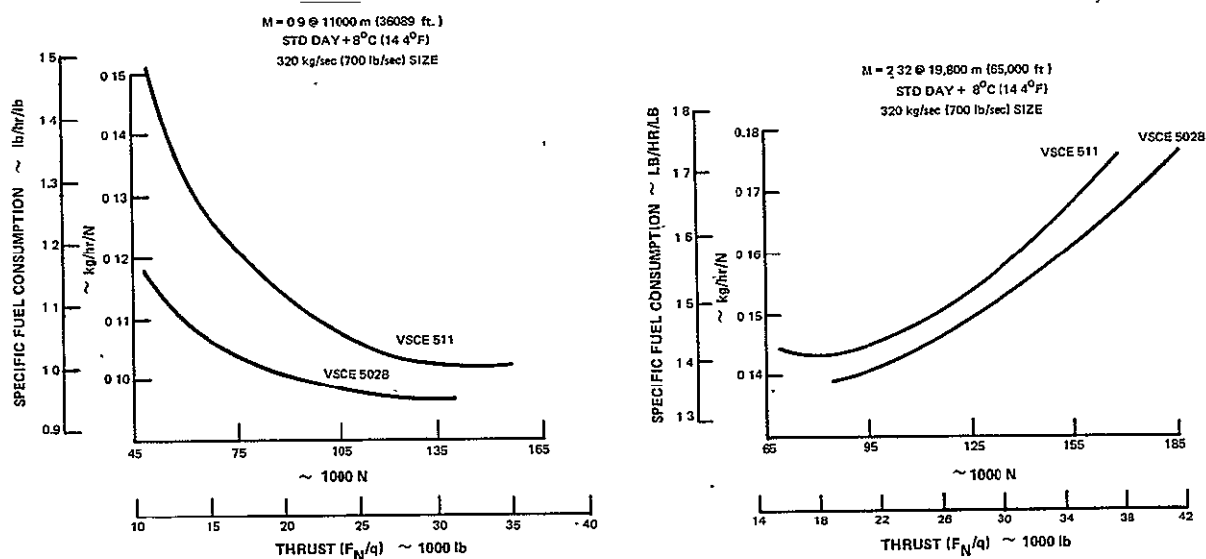


Figure 4.2-1 Installed VSCE-502B and VSCE-511 Supersonic and Subsonic Performance Characteristics

	<u>Pod Weight ~ kg (lbm)</u>	
	<u>VSCE-511</u>	<u>VSCE-502B</u>
Engine + Nozzle	6990 (15400)	6080 (13400)
Inlet (2.4-1)	1750 (3850)	1750 (3850)
Cowl	420 (920)	420 (920)
Support Structure	480 (1050)	430 (940)
Total per pod	9640 (21220)	8670 (19110)
per airplane	38500 (84880)	34670 (76440)

The data reflect pod weight only; verticle tail size, gear lengths, wing flutter material, balance, etc. were not evaluated.

Range versus engine size for VSCE-510, VSCE-511 and VSCE-502B is shown in Figure 4.2-2. At the maximum range engine size of 290 kg/sec (650 lb/sec) the VSCE-511 shows a range deficit of about 560 km (300 n.mi.) compared to VSCE-502B. Transonic thrust margins exceed the minimum requirement of 0.3 in all three cases. The range deficit of the VSCE-511 resulted from an 11% increase in propulsion weight, a 1.8% increase in supersonic TSFC and an 8.5% increase in subsonic TSFC.

4.2.1.2 Evaluation of Nearer Term Rear-Valve VCE

P&WA provided nearer term technology versions of the VSCE engines, as described earlier, and Boeing generated appropriate engine performance increments for the rear-valve VCE engine, using the VSCE technology increments. These increments are summarized in Table 4.2-V.

With these inputs, performance was calculated for several variations of a nearer term VCE-112C. Thrust/TSFC characteristics of these engines are shown in Figure 4.2-3. The best of these, VCE-112-NT2, is compared to VCE-112C and both near and far term versions of the VSCE cycle in Figure 4.2-4. When each engine is sized for optimum airplane performance the VCE cycle suffers larger TSFC penalties than the VSCE cycle. On this basis, it was concluded that: 1) a mission analysis comparison was not warranted, and 2) the rear-valve VCE cycle would not out-perform the VSCE for this design Mach number for any technology level of interest.

4.2.1.3 VSCE-502B Engine Jet Noise

An effort was made to define advanced take-off systems and procedures which would minimize community and/or sideline noise. The Model 733-630 airplane with 320 kg/sec (700 lb/sec) VSCE-502B engines at 340,190 kg (750,000 lb.) TOGW was used for this analysis. The effect on sideline and community noise levels of using advanced takeoff procedures and systems compared to current FAR 35 procedures is shown in Figure 4.2-5. The cross-hatched area shows the reduced noise levels after the coannular effects have been applied. The data show that using FAR 36 rules and an engine thrust to achieve a takeoff field length of 3660 m (12,000 ft) the SAE prediction methods gives a sideline noise level of 117 EPNdB and a community noise level of 120 EPNdB. Coannular benefits reduce the levels to 109 and 115 for the sideline and community respectively. Hence the coannular effect can reduce

sideline noise to FAR 36 "traded" noise levels with a small, cruise-sized variable cycle engine. However, the community noise level is much too high. These data also show that by using advanced systems and procedures to minimize community noise the community noise level can be reduced to only 105 EPNdB (including the coannular benefit). This advanced takeoff and climbout involves:

- Maximum thrust (within sideline noise constraints) during ground roll, taking advantage of ground shielding
- Thrust reduction during climb (programmed throttles) to control sideline noise
- Flap retraction during climb (programmed flaps) for better lift/drag ratio
- Acceleration during climb to improve lift-drag ratio
- Cutback at community to less than 3 engine level flight thrust. If an engine fails at this point, APR automatically increases thrust to level flight power setting.

Note that the takeoff field length has been decreased from 3660 m (12,000 ft) to 3200 m (10,500 ft) since power has increased during the ground roll to take advantage of ground shielding. An alternate procedure is shown to minimize sideline noise. Here power is reduced during ground roll consistent with a takeoff field length of 3660 m (12,000 ft). Sideline noise is reduced 4 EPNdB. This will result in less acceleration to the community, a lower lift-drag ratio and more noise at cutback, about 5 EPNdB. These data show that advanced takeoff procedures and systems have the potential to achieve community noise levels below FAR 36 and can provide flexibility to trade sideline and community noise levels to suit individual airport requirements.

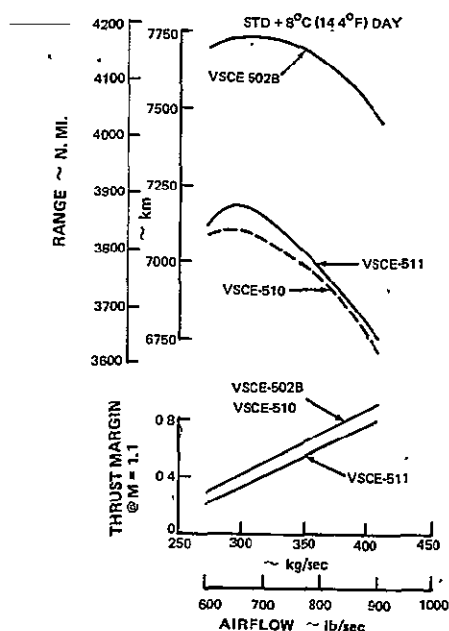


Figure 4.2-2 Comparison of Range Versus Engine Size for the VSCE-510, 511, and 502B Engine Concepts

TABLE 4.2-V

VCE-112B COMPONENT CHANGES TO
NEAR TERM TECHNOLOGY LEVELS

	Far Term	Near Term
Maximum Primary Burner Temperature °C (°F)	1540 (2800)	→ 1430 (2600)
Fan Bleed		
(Cooling Air for Second LP Turbine) °C (°F)		
Maximum Duct Burner Temp. = 1080 (1900)	1.8%	→ 5%
Maximum Duct Burner Temp. = 1200 (2200)		→ 8.2%
HP Compressor Bleed		
(Cooling Air For HP Turbine And First LP Turbine)	10.7%	→ 18%
Maximum HP Compressor Bleed Air	700 (1300)	→ 620 (1150)
Temperature at Mach 2.32, 16150m (53,000 ft) °C (°F)		
T _{amb} = 8°C (14.4°F)		
Rotating Component Design Point		
Adiabatic Efficiencies	-1%	-1%
Duct Burner Thrust Effective Efficiency	0.995	→ 0.945

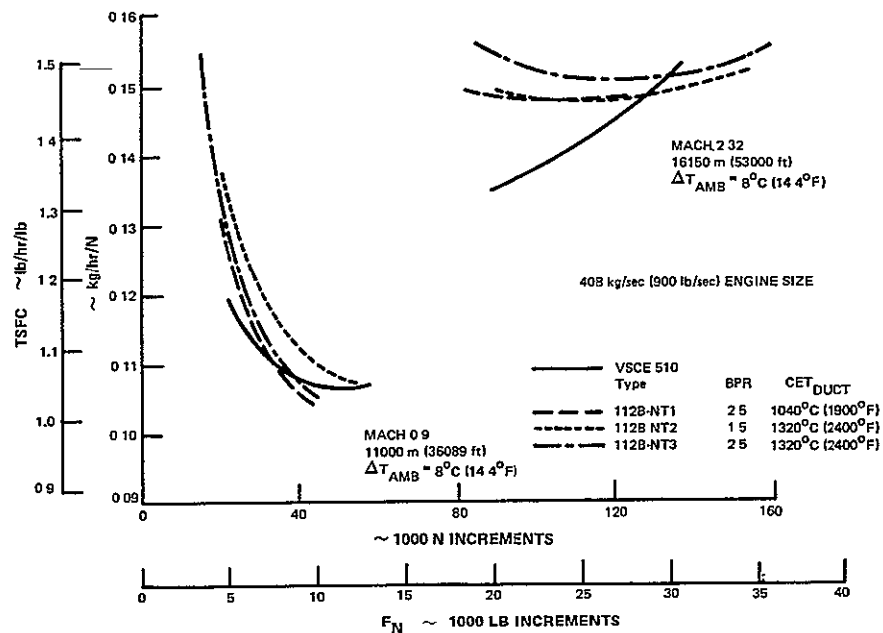


Figure 4.2-3 Engine Thrust Versus Fuel Consumption Characteristics of Nearer-Term Technology Rear-Valve VCE Concepts

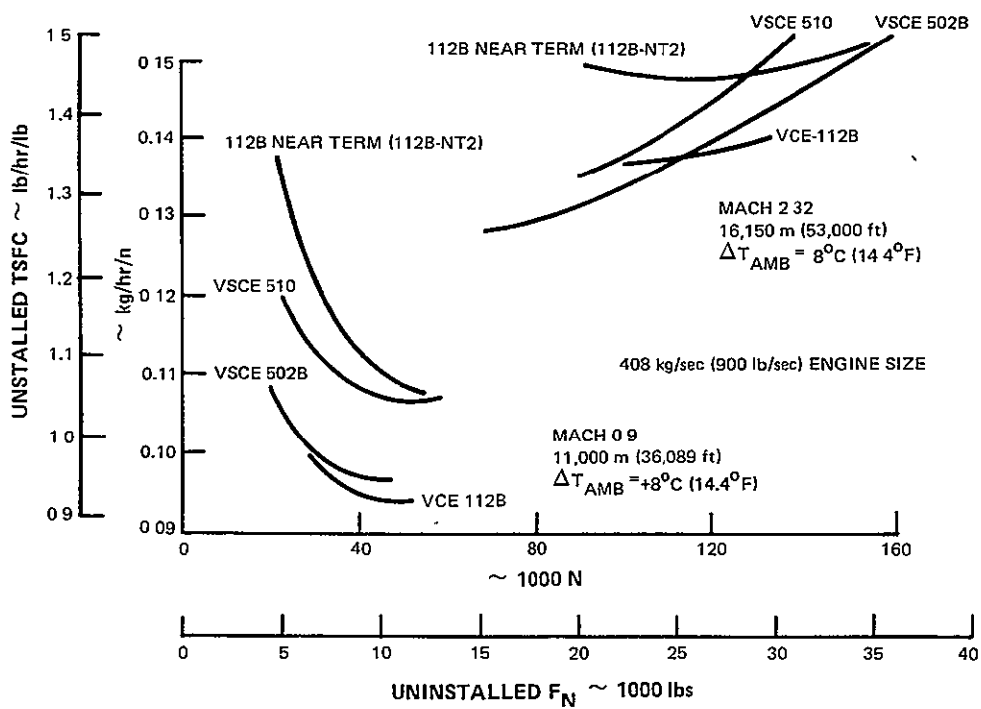


Figure 4.2-4 Thrust Versus Fuel Consumption Comparison of VCE and VSCE Cycles

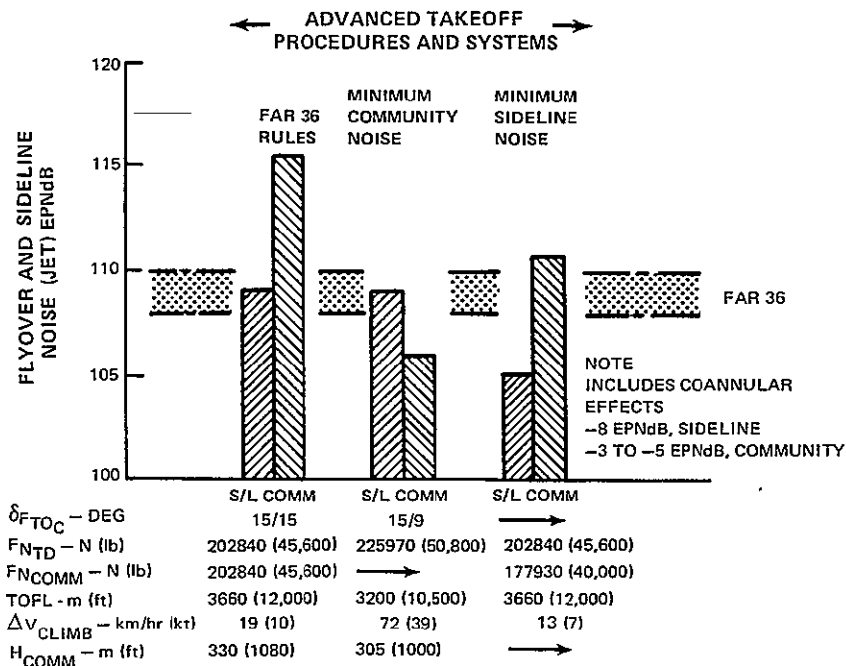


Figure 4.2-5 Jet Noise Characteristics Using Advanced Procedures and Systems

The question of whether or not the inclusion of the real duct heater temperature profile (with cool air near the wall) could affect the coannular noise characteristics or supersonic cruise performance of the VSCE-502B engine was investigated. Coannular jet noise has been measured in model tests with essentially square velocity profiles in the duct heater exhaust stream. Duct heaters typically produce non-uniform velocity profiles in the duct heater exhaust stream. The jet noise measured in model tests, with ideal profiles, may not be representative of the actual VSCE-502B because of the reduced shear velocity at the boundary of the duct stream, which may diminish its rate of decay.

Boeing has developed computer simulations of the VSCE-502B with approximations of the real duct heater temperature profiles and with ideal temperature profiles. The real profile was approximated with a two step profile (cool wall air, hot core air). The amount of wall cooling air needed to produce the 4% thrust loss associated with profile effects was found to be 16.5% of the fan duct airflow. Schematics of the resultant profiles are shown in Figure 4.2-6, along with a representation of a real profile.

These simulations of the VSCE-502B have been run at take-off and supersonic cruise conditions with various augmentor temperatures. Results show that the method used by P&WA to represent real profile effects for the augmentor, in terms of thrust effective efficiency for the burner, appears to be a reasonably accurate representation for thrust - TSFC characteristics.

The same type of simulation was used to address the problem of duct burner temperature profile effect on noise. A schematic of the way the "real" velocity profile of the VSCE-502B was simulated is shown in Figure 4.2-7. Streams 1 and 3 represent duct wall cooling air; stream 2 is the heated duct stream, and stream 4 is the primary stream. Also shown in Figure 4.2-7 is a representation of a VSCE-502B ideal velocity profile. Noise was calculated for each of these velocity profiles at two thrust levels. Results of these calculations indicate a maximum increase in sound pressure level of +0.3 dB for the real profile over the ideal profile noise when the outer cooling flow is 10% or less of the duct flow and the inner cooling flow is 6.5% or less of the duct flow.

The conclusion reached is that for reasonable cooling flow levels (stream 1 less than 10% of duct flow and stream 3 less than 6.5%) the acoustic effect will be very small and within the range of normal measurement error.

4.2.1.4 Inlet/Engine Airflow Match

During the contract period, a revised Boeing inlet definition study was in progress which altered the inlet mass flow characteristics. A check was made to determine if the VSCE-502B maximum flow demand was still compatible with the inlet supply. A plot of the revised inlet mass flow characteristics is shown in Figure 4.2-8. Inlet mass flow freestream area (A_0 to inlet lip area (A_1) ratio is plotted versus local Mach number for a standard day free stream inlet design Mach number of 2.4. The increment between the "inlet captive mass flow" line and the "flow available to engine" line represents the bleed, vortex valve control flow, and leakage. Engine mass flow requirements for the VSCE-502B are shown by the triangular symbols. It can be seen that the inlet supply matches the engine demand very closely, and therefore no revisions to the engine airflow demand schedule are required.

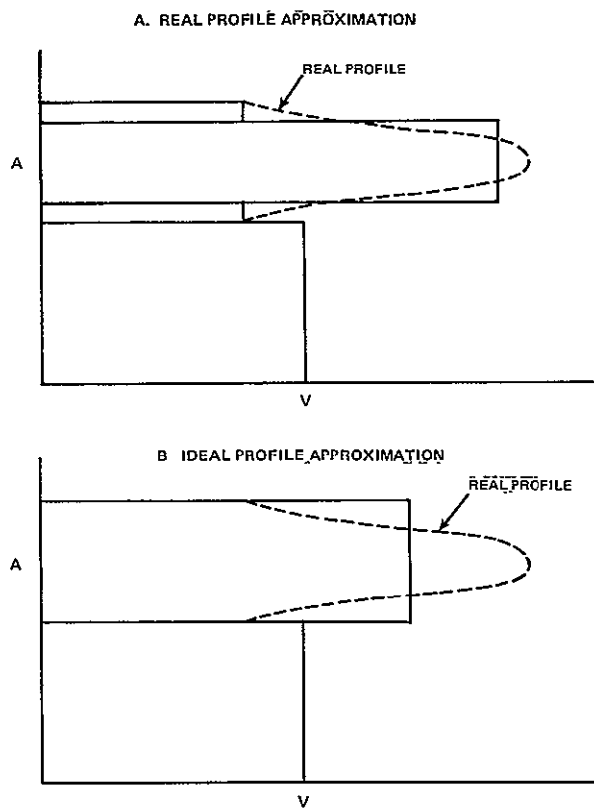
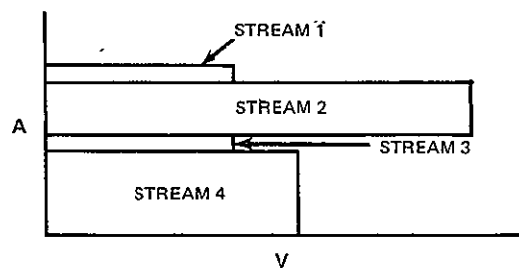


Figure 4.2-6 Approximation of Real and Ideal Duct Burner Temperature Profiles

REAL DUCT BURNER VELOCITY PROFILE APPROXIMATION
P&WA -502B ENGINE



IDEAL DUCT BURNER VELOCITY PROFILE,
P&WA -502B ENGINE

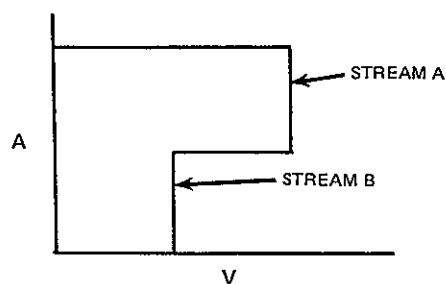


Figure 4.2-7 Approximation of Real and Ideal Duct Burner Velocity Profiles

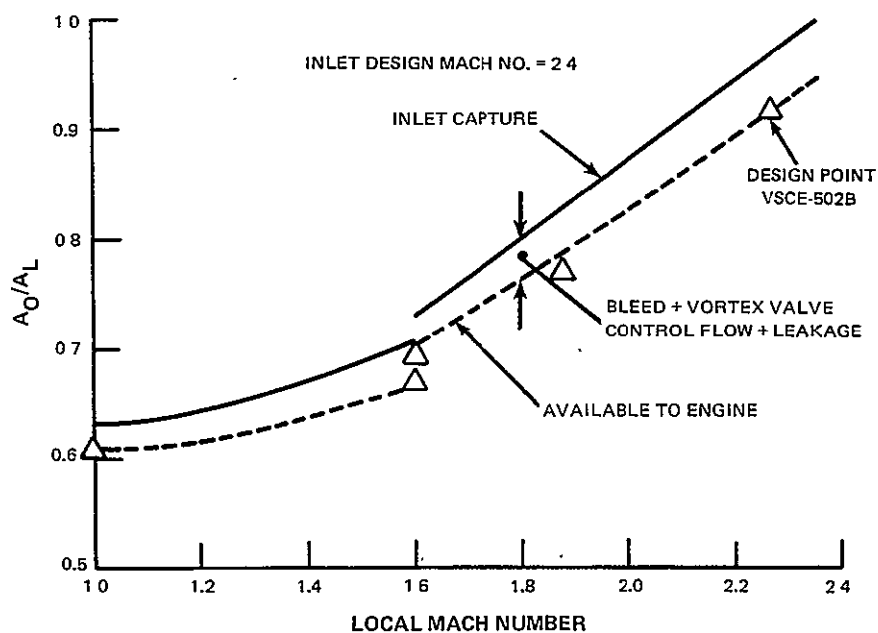


Figure 4.2-8 Standard Day Inlet Mass Flow Characteristics

4.2.1.5 Engine Cycle/Airplane Sensitivities

The sensitivity of the VSCE-502B to selected component performance shortfalls was evaluated. P&WA provided a list of engine component efficiency decrements, with corresponding increases in subsonic and supersonic TSFC at typical cruise thrust levels. An increment in engine weight was also evaluated; however, the 4 dB engine noise increase that was provided was not evaluated. The effect of these shortfalls was measured in terms of loss in airplane design mission range at constant maximum taxi weight. Section 4.3.2 describes these technology sensitivity factors.

Sensitivity of the Boeing advanced supersonic airplane to increases in TSFC and engine weight is shown in Figure 4.2-9. The comparison between sensitivity to subsonic and supersonic cruise TSFC shown in this figure is not a true measure of the relative importance of these factors, since the only subsonic increment in the design mission is a cruise-to-alternate leg. In any real life airline operation, with most flights at less than design range and with subsonic cruise legs added, the subsonic efficiency takes on an added importance. Therefore, the data in Figure 4.2-9 should not be used to define break-even trade factors between subsonic and supersonic performance for cycle optimization. Airline economic studies will be required to establish realistic factors for engine weight and efficiency trade studies.

The engine component technology increments provided by P&WA are listed in Table 4.2-VI along with the resultant range loss. The technology increment levels are not intended to represent a confidence level or tolerance. For the factors shown, the significance of sensitivity of range to nozzle thrust coefficient is obvious.

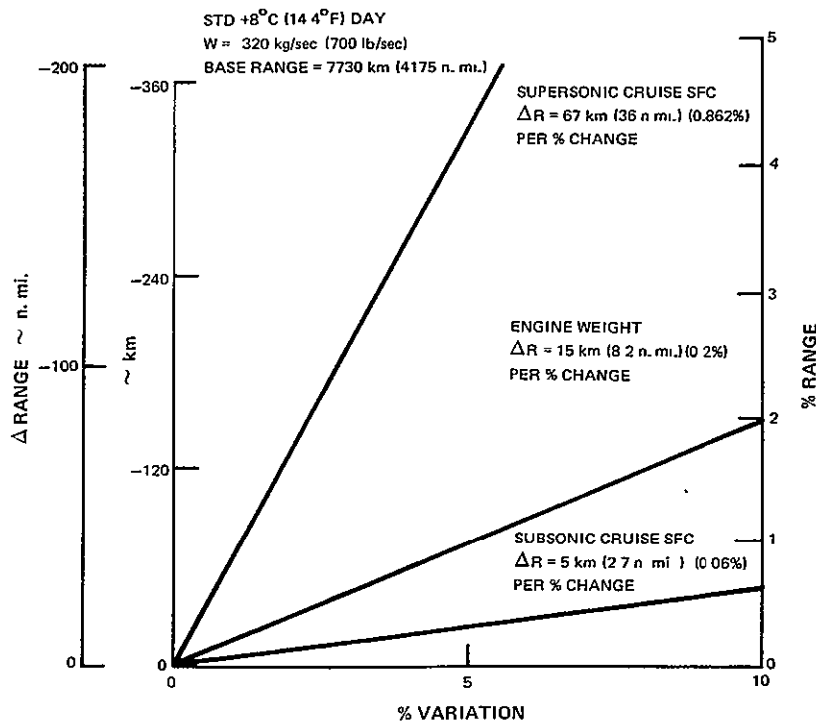


Figure 4.2-9 Sensitivity of the Boeing Advanced Supersonic Airplane to Increases in Thrust Specific Fuel Consumption and Engine Weight

TABLE 4.2-VI

BOEING RANGE SENSITIVITIES
VSCE-502B TECHNOLOGY INCREMENTS

Component or Item	Δ Tech	Range Loss* — km (n. mi.) (%)
1. Turbine Cooling	+1% W_{AE} Vane +1% W_{AE} Blade -0.5% η_{HPT}	49 (26.6) (0.64) Supersonic Cruise 3 (1.6) (0.04) Subsonic Cruise 52 (28.2) (0.68) Total
2. Nozzle Thrust Coefficient	-1%	237 (128.2) (3.07) Supersonic Cruise 9 (4.8) (0.11) Subsonic Cruise 246 (133.0) (3.18) Total
3. Duct Burner Efficiency	-1%	27 (14.4) (0.34) Supersonic Cruise
4. Engine & Nozzle Weight	+2%	30 (16.4) (0.39)

*Base Range = 7730 km (4175 n. mi.)

4.2.2 Douglas Integration Study

The Douglas Integration Study concentrated on three areas: engine selection, engine/nacelle integration, and engine technology sensitivity. This study was performed using the Douglas 2.2 Mn baseline AST aircraft.

4.2.2.1 Engine Selection

To select the engine cycle for the integration study, an analysis of the installed characteristics of the rear-valve VCE-112CD was required to permit comparison with the VSCE cycle. VCE-112CD is the Douglas designation for the VCE-112C.

Analysis of VCE-112CD

Douglas analysis indicated that a VCE-112CD engine size of 380 kg/sec (834 lbm/sec) sea level corrected airflow was necessary to meet take-off thrust 231.3 kN (52,000 lb) at sea level, Mn 0.3, uninstalled) and FAR Part 36 sideline and cutback traded noise levels for their 340190 kg (750,000 lbm) TOGW aircraft. Figure 4.2-10 shows VCE-112CD in this flow size as installed with the Douglas external compression inlet. The uninstalled engine data supplied by Pratt & Whitney Aircraft were combined with inlet performance and drag characteristics and an estimate of the nacelle drag to produce required installed propulsion system performance. The inlet performance and nacelle analysis included an evaluation of the following items:

- Inlet spillage drag
- Inlet bypass drag
- Engine compartment ventilation and ECS cooling airflow drag
- Nacelle skin friction drag
- Nacelle afterbody drag
- Nacelle wave drag

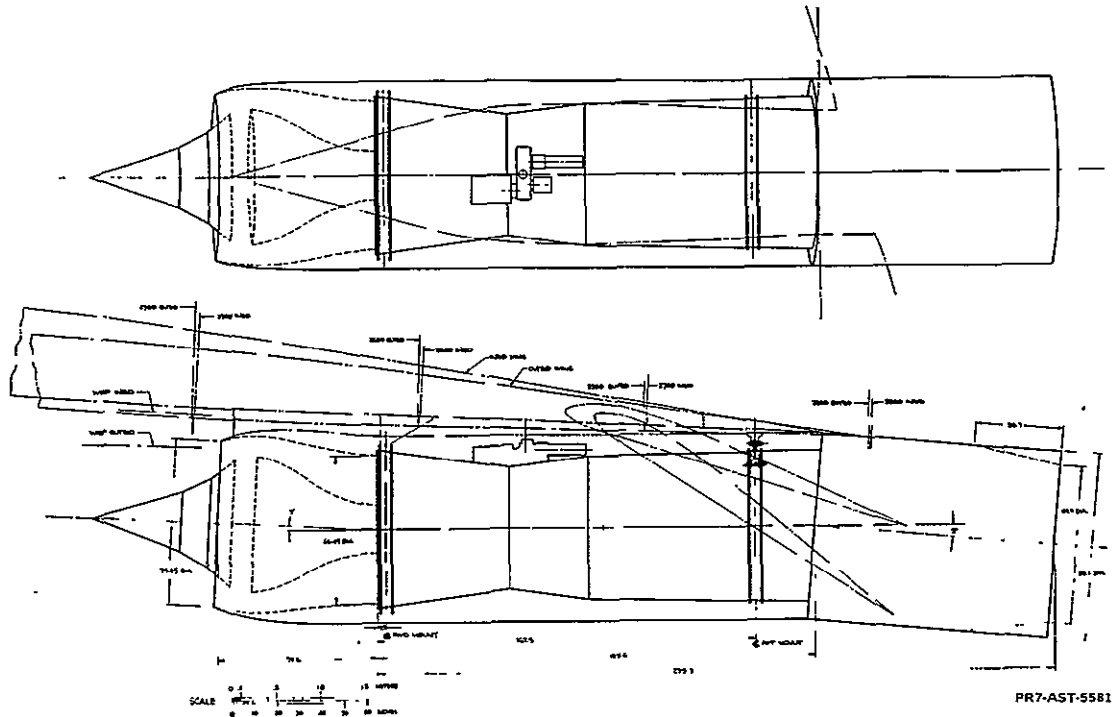


Figure 4.2-10 Installation Drawing of Rear-Valve VCE-112CD Engine

Examples of propulsion system installed performance, as described above, can be found in Figure 4.2-11 for subsonic and supersonic cruise conditions.

Installation of the VCE-112CD in four axisymmetric nacelles was evaluated on the baseline airframe. Engine location on the wing was based on aerodynamic, structural, acoustic, and control surface location considerations. It was also found that full circumferential openings could not be used for thrust reversing due to interference problems with fully deployed wing flaps. The only areas found to be available for thrust reversing were 90° on the top and 150° on the bottom of the engine nozzle.

The engine was mounted on the wing by a three point attachment structure. The axisymmetric intakes were mounted to the engine casing and divorced from the wing structure. A weight comparison of the VCE-112CD powered aircraft (configuration 5L) with the baseline turbojet powered 5A configuration is shown in Tables 4.2-VIIA and B. The engine defined for the baseline airplane is based on data obtained from the engine manufacturers during the 1973 NASA engine contract studies. From a screening of these data it had been concluded that the dry turbojet incorporating 1975 technology was the most promising from the standpoint of providing a minimum operating cost design. A conceptual turbojet engine was, therefore, sized to meet FAR Part 36 noise constraints and an in-house engine deck was derived and utilized in the determination of airplane performance. Most of the weight decrease was due to the 26% lower engine plus nozzle weight of the VCE-112CD. The inlet/nacelle weight increase of 6% for the VCE-112CD was caused by a larger capture area and increased engine cowl area.

The structural weight decrease of (675 kg (1490 lbm)) for configuration 5L includes a difference in pylon and engine support weight, along with differences in wing and fuselage weight caused by changes in load. Since the baseline aircraft maximum rotation was limited by engine to ground clearance, the shorter installation of VCE-112CD allowed a reduction in landing gear length, saving 1.15% in gear weight. The total OEW saving over the 5A baseline was 5.9%.

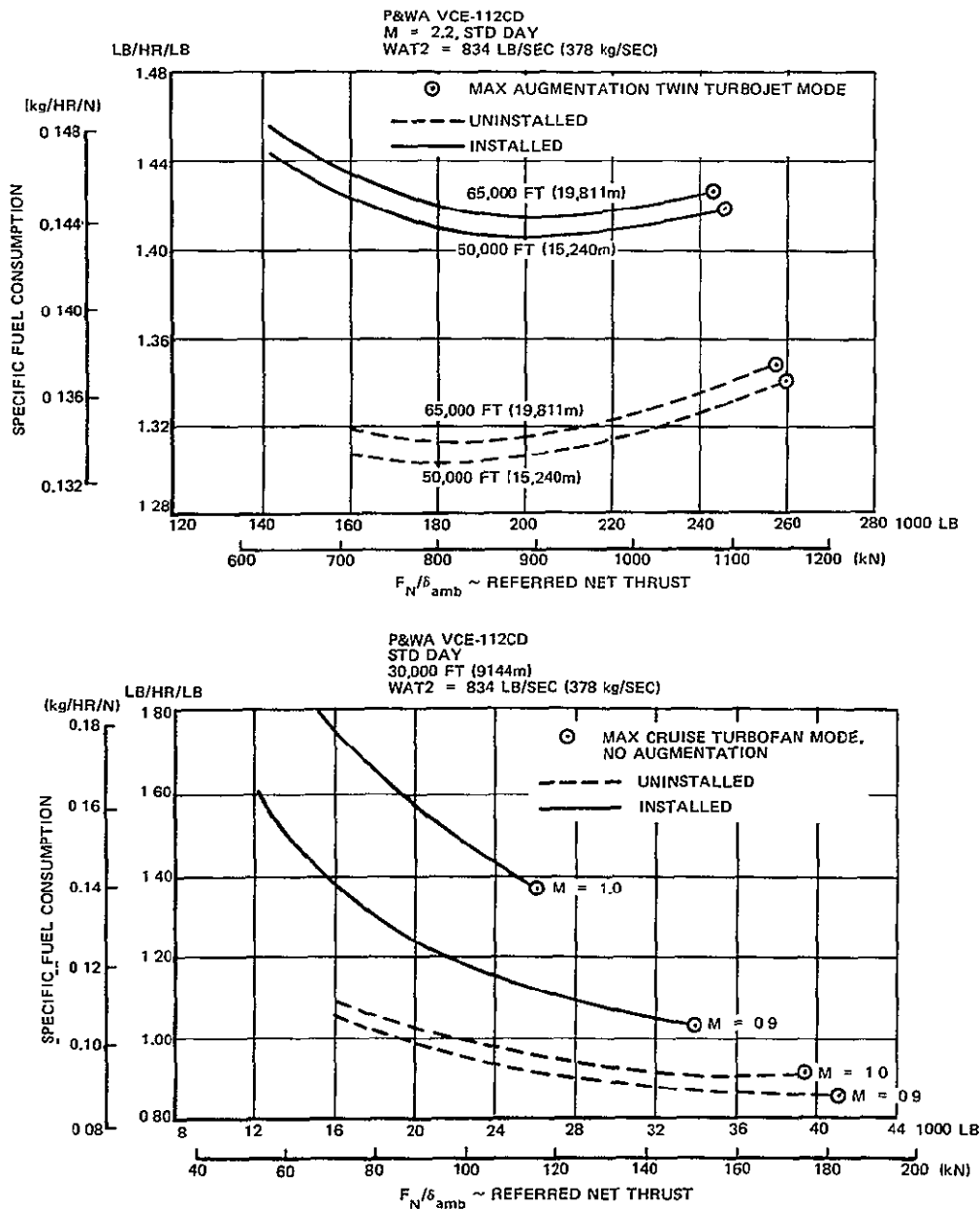


Figure 4.2-11 Rear-Valve VCE-112CD Installed Performance

TABLE 4.2-VIIA

WEIGHT COMPARISON – CONFIGURATION 5L
(VCE-112CD POWERED AIRCRAFT)
WITH 5A BASELINE (TURBOJET POWERED AIRCRAFT)
U. S. UNITS

Configuration Item	Weight ~ lbm		
	5A Turbojet	5L VCE-112CD	Difference
Wing	75,347	75,281	-66
H-Tail	3,960	3,960*	0
V-Tail	3,807	3,807*	0
Fuselage	47,713	47,696	-17
Landing Gear	36,792	36,370	-422
Flight Controls	9,115	9,115	0
Nacelle/Inlet	14,730	15,649	+919
Propulsion (Less Fuel System)	70,190	52,278	-17,912
Fuel System	3,820	3,820	0
Emergency Power Unit	950	950	0
Instruments	1,227	1,227	0
Hydraulics	5,684	5,684	0
Pneumatics	1,332	1,332	0
Electrical	4,850	4,850	0
Navigation and Communications System	2,756	2,756	0
Furnishings	24,478	24,478	0
Air Conditioning	4,854	4,854	0
Ice Protection	489	489	0
Handling Provisions	90	90	0
Penalty - Flutter and Aeroelasticity	2,860**	2,860	0
Structural Weight Increment	—	-1,490	-1,490
Manufacturer's Empty Weight (MEW)	315,044	296,056	-18,988
Operational Items	8,096	8,096	0
Operational Empty Weight (OEW)	323,140	304,152	-18,988

* The weight increment for strength, etc., for these items is included under the item structural weight increment and listed separately.

** 2000 lb for roll and control effectiveness, 860 lb for flutter optimization.

TABLE 4.2-VIIB

WEIGHT COMPARISON – CONFIGURATION 5L
(VCE-112CD POWERED AIRCRAFT)
WITH 5A BASELINE (TURBOJET POWERED AIRCRAFT)
SI UNITS

Configuration Item	Weight ~ kg		
	5A Turbojet	5L VCE-112CD	Difference
Wing	34,177	34,147	-30
H-Tail	1,796	1,796*	0
V-Tail	1,727	1,727	0
Fuselage	21,643	21,635	-8
Landing Gear	16,689	16,498	-191
Flight Controls	4,135	4,135	0
Nacelle/Inlet	6,682	7,099	+417
Propulsion (Less Fuel System)	31,838	23,713	-8,125
Fuel System	1,733	1,733	0
Emergency Power Unit	431	431	0
Instruments	557	557	0
Hydraulics	2,578	2,578	0
Pneumatics	604	604	0
Electrical	2,200	2,200	0
Navigation and Communications System	1,250	1,250	0
Furnishings	11,103	11,103	0
Air Conditions	2,202	2,202	0
Ice Protection	222	222	0
Handling Provisions	41	41	0
Penalty - Flutter and Aeroelasticity	1,297**	1,297	0
Structural Weight Increment	—	-676	-676
Manufacturer's Empty Weight (MEW)	142,905	134,294	-8,613
Operational Items	3,672	3,672	0
Operational Empty Weight (OEW)	146,577	137,966	-8,613

* The weight increment for strength etc., for these items is included under the item Structural Weight Increment and listed separately.

** 907 kg for roll and control effectiveness, 390 kg for flutter optimization.

The supersonic wave drag for the VCE-112CD configuration was estimated to be 5.0 drag counts ($\Delta C_D = .00050$) less than the baseline (5A) configuration. Nacelle skin friction drag was included in installed engine performance. Trimmed lift and drag characteristics for the VCE-112CD powered aircraft were obtained by subtracting the wave drag increment from the wave drag of the baseline turbojet powered aircraft.

Estimated mission performance for the VCE-112CD powered aircraft is shown in Figure 4.2-12. Mission profile and fuel reserve ground rules were the same as used for the baseline aircraft (Figure 4.2-13). Take-off gross weight (TOGW) was held constant at 335,660 kg (740,000 lbm) and payload was fixed at 25,385 kg (55,965 lbm). The selected engine size noted in Figure 4.2-14 (380 kg/sec (834 lbm/sec)) was the minimum size that would meet FAR Part 36 noise requirements and take-off thrust requirements. The optimum unconstrained engine size for range was 310 kg/sec (685 lbm/sec).

Engine Cycle Selection

Estimated mission performance for both VSCE-502BD and VCE-112CD powered aircraft is presented in Figure 4.2-14. In each case, TOGW was held constant at 340,190 kg (750,000 lbm) and payload 25,265 kg (55,695 lbm). The VSCE-502BD engine, sized at 342 kg/sec (754 lbm/sec) to meet noise and take-off thrust requirements, produced a range of 8700 km (4700 n.mi.). The VCE-112CD engine, sized at 378 kg/sec (834 lbm/sec) by noise and take-off thrust requirements, produced a range of 8270 km (4465 n. mi.). Based on this 435 km (235 n. mi.) range advantage, the VSCE-502BD engine was selected for the remainder of the integration study.

4.2.2.2 Nacelle/Engine Structural Study

The purpose of this portion of the study was to compare a structural and a non-structural nacelle to determine which would result in least overall weight, and to refine the chosen configuration. A mixed compression inlet was chosen for this portion of the study.

The VSCE-502BD has mount points in the upper portion of the forward and aft mounting flanges. The front mount takes vertical, side, thrust, and torque loads, while the rear mount takes vertical and some torsion loads. The engine was not designed to support an inlet and would require additional structural weight if the inlet was mounted on its front flange.

Engine and airframe accessory locations are identical in both structural and non-structural nacelles. Engine accessories are located on the top of the engine while airframe accessories are located in the wing just outboard of the nacelle. The airframe accessories are driven by shafting from the engine driven gearbox power takeoff.

The non-structural nacelle/engine installation, consisting of a mixed compression inlet mounted directly to the forward engine flange, is shown in Figure 4.2-15. The nacelle is comprised of left and right, fore and aft non-structural access doors which are hung from the pylon/splitter. The engine is mounted directly to the wing/pylon through fore and aft mounts.

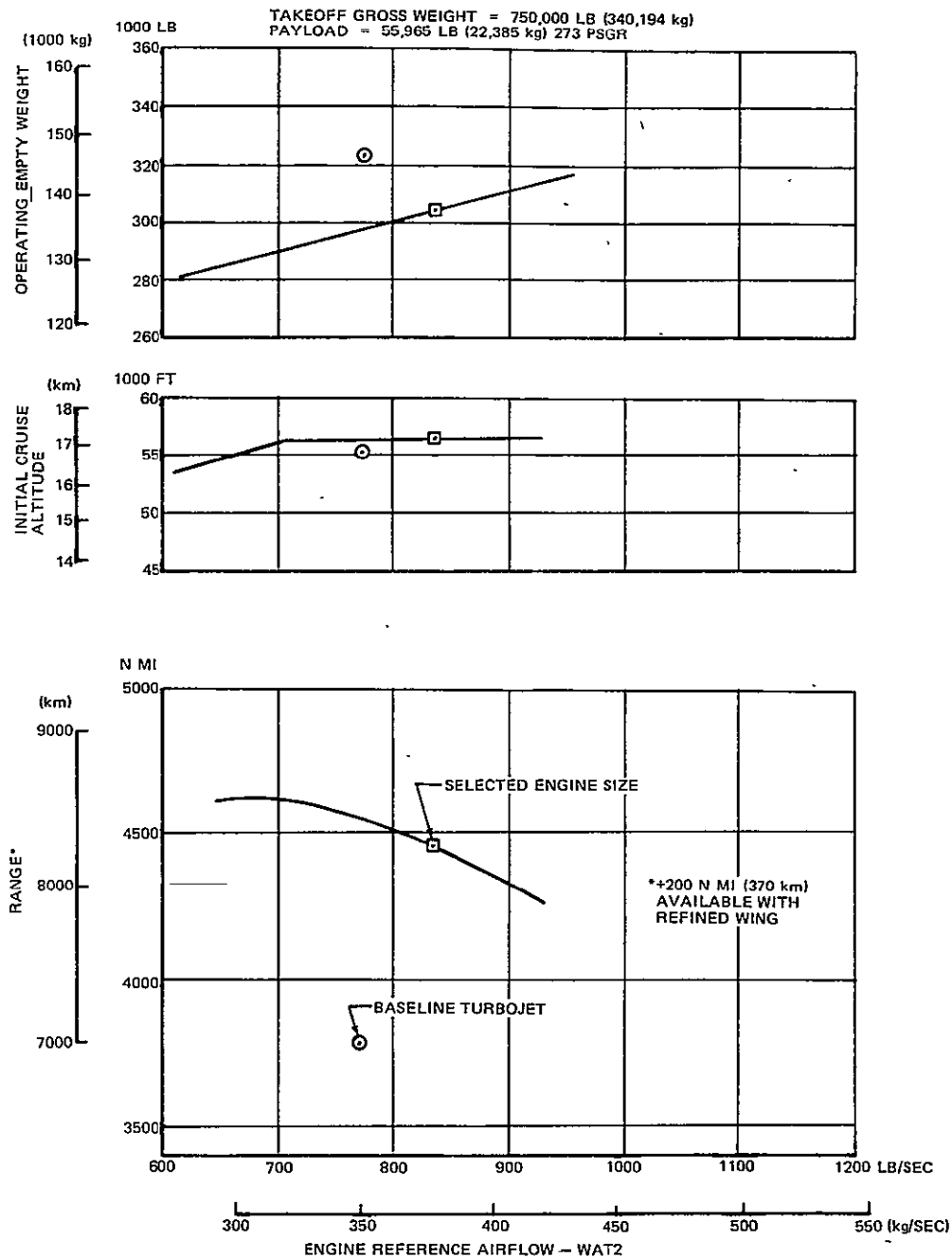


Figure 4.2-12 Effect of Rear Valve VCE-112CD Engine Size on Mission Performance

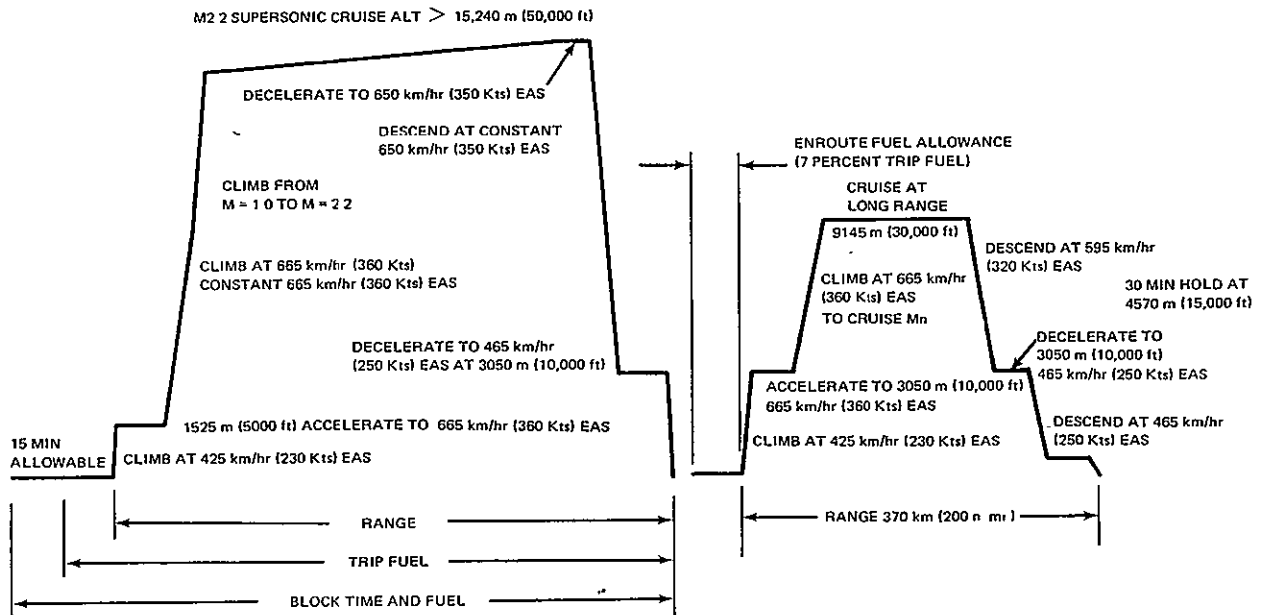


Figure 4.2-13 Mission Profile

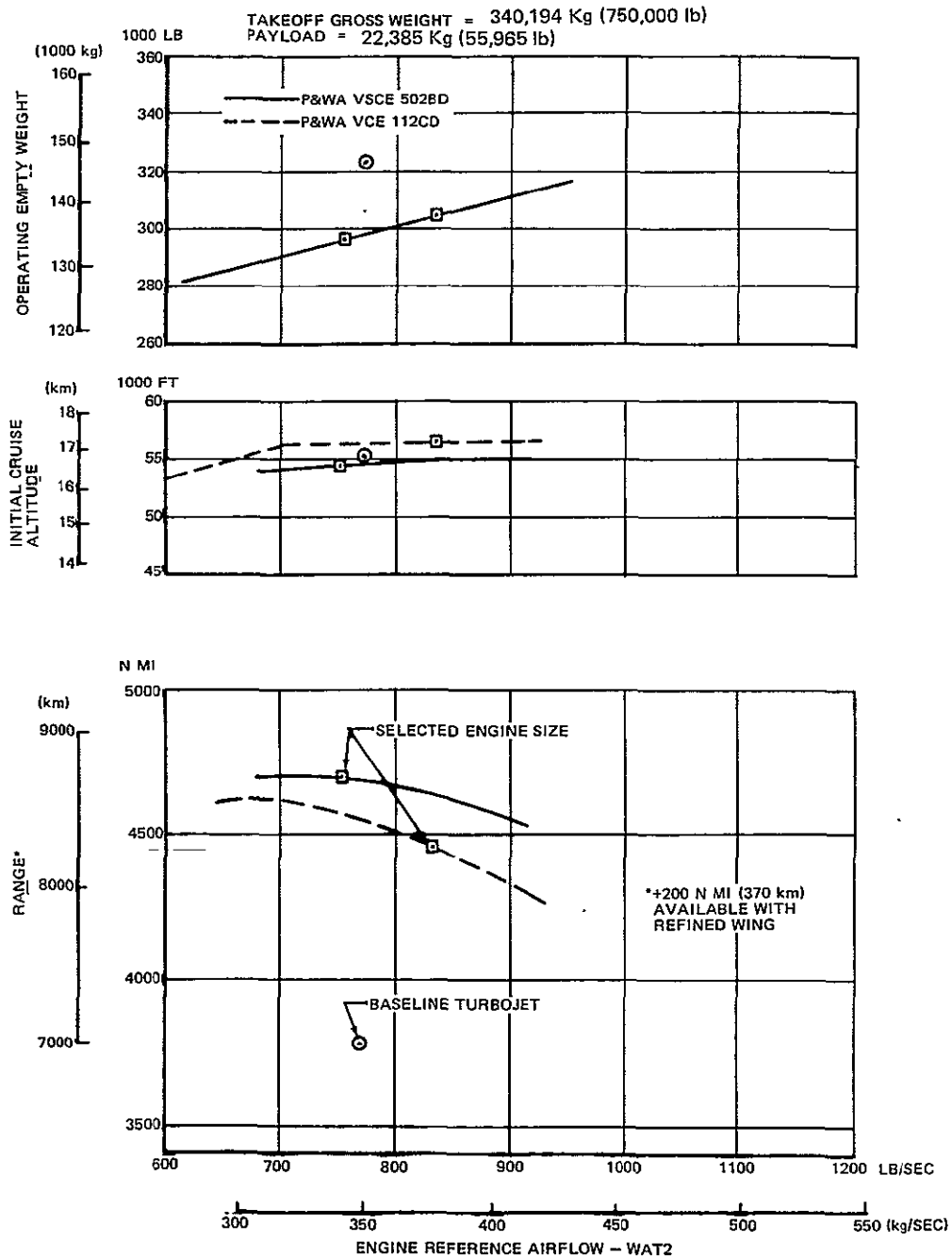


Figure 4.2-14 VSCE and Rear-Valve VCE Comparison

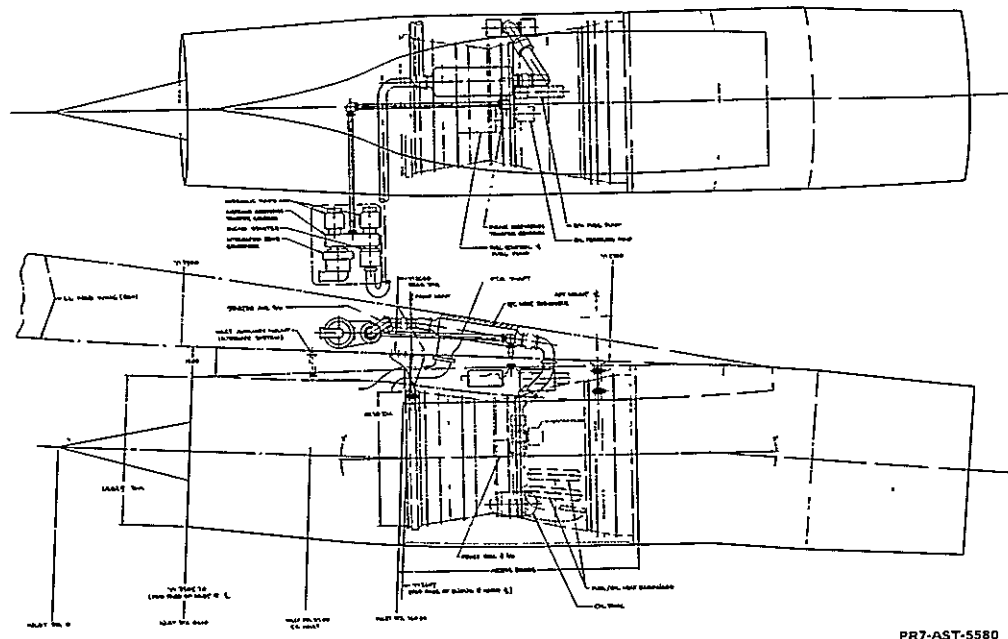


Figure 4.2-15 Non-Structural Nacelle/Engine Installation

The structural nacelle/engine installation consists of a mixed compression inlet mounted on the airframe/wing structure (Figure 4.2-16). The upper part of the nacelle is a fixed structural cowl which may be integral with the pylon/splitter and wing. The lower half consists of left and right hand access doors which are hung from the upper cowl. The engine is mounted at the forward end on the inlet structural mount. This forward mount system allows relative movement between inlet and the engine face. Distortion is not considered a problem. The aft mount is attached directly to the wing/pylon.

Table 4.2-VIII shows a weight comparison of structural and non-structural nacelle concepts. The structural nacelle results in a slightly lighter installation because the inlet is not directly attached to the engine. The structural nacelle was chosen for further refinement mainly because of separation of inlet and engine so that the engine doesn't carry inlet loads and can be removed without removing the inlet.

4.2.2.3 Technology Assessment

The impact of engine critical technology items on aircraft range was assessed for the VSCE-502B in the Douglas Mach 2.2 baseline supersonic cruise transport. Range sensitivity factors for this aircraft are shown in Table 4.2-IX. Pratt & Whitney Aircraft generated engine performance sensitivity factors for the VSCE-502B are shown in Table 4.2-X and are described in Section 4.3.2. Table 4.2-XI presents the effects of these engine performance sensitivities on aircraft range. As shown in Table 4.2-XI, nozzle performance and a decrease in coannular noise benefits have the most significant effect on aircraft performance.

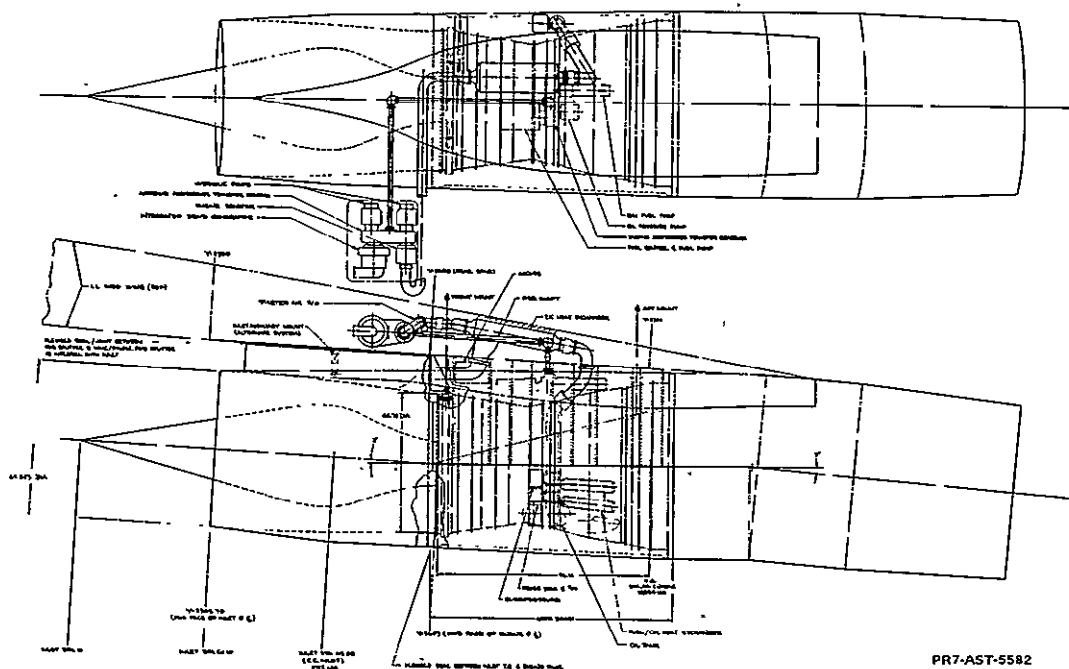


Figure 4.2-16 Structural Nacelle/Engine Installation

TABLE 4.2-VIII

NACELLE CONCEPT WEIGHT COMPARISON
MIXED COMPRESSION INLET, VSCE-502BD [342 kg (754 lbm)]
NACELLE STRUCTURE STUDY

	Weight ~ kg (lbm)	
	Non-Structural Nacelle	Structural Nacelle
Inlet & Spike	792.0 (1,746)	823.3 (1,815)
Nacelle Structure	259.0 (571)	279.9 (617)
Engine Mounts & Misc.	172.8 (381)	124.7 (275)
Nacelle & Inlet Weight	1223.8 (2,698)	1227.9 (2,707)
Engine/Nozzle/Suppressor	4959.7 (10,934)	4914.3 (10,834)
Engine Systems	251.7 (555)	251.7 (555)
Propulsion Weight	5211.4 (11,489)	5166.0 (11,389)
Total Nacelle, Inlet & Propulsion	6435.2 (14,187)	6393.9 (14,096)

TABLE 4.2-IX

AIRPLANE RANGE FACTORS FOR VSCE-502B
 SIZED FOR 342 kg/sec (754 lb/sec), 86 km
 (53.4 mi) PER 1000 kg (2205 lbs)

- 78 km (21 n. mi.) per 1000 lb of weight
- 78 km (42 n. mi.) per 1 percent TSFC at 2.2M cruise
- 67 km (36 n. mi.) per drag count at 2.2M cruise
- 7.5 km (4 n. mi.) per 1 percent TSFC at subsonic cruise

TABLE 4.2-X

P&WA VSCE TECHNOLOGY SENSITIVITY EVALUATION

Component Change		VSCE-502B	
Engine		11,000 m	16,155 m
Flight Condition		(36,089 ft) 0.9 Mn	(53,000 ft) 2.2 Mn
Power Setting		75% MCR, Duct Burner Not Lit	60% MCR, Duct Burner Lit
		% Δ TSFC	
1.	Increase in Turbine Cooling Air		
	+1% W_{ae} in First-Stage Vane		
	+1% W_{ae} in First-Stage Blade		
	-0.5% High Turbine Efficiency	+0.59%	+0.64%
2.	Decrease in Nozzle Performance		
	-1 pt. C_V	+1.78%	+3.44%
3.	Decrease in Duct Burner Efficiency		
	-1 pt.	0	+0.28%
4.	Decrease in Coannular Noise Benefit	—	—
	-4 PNdB		
5.	Increase in Engine + Nozzle/Reverser Weight +2%	—	—

TABLE 4.2-XI

DOUGLAS RANGE SENSITIVITIES
VSCE-502B TECHNOLOGY INCREMENTS

Item	Range Δ — km (n. mi.)	
	Subsonic Cruise Δ TSFC Effect	Supersonic Cruise Δ TSFC Effect
1. Increase in Turbine Cooling Air	4 (2)	50 (27)
2. Decrease in Nozzle Performance (1%)	13 (7)	269 (145)
3. Decrease in Duct Burner Efficiency (1%)	0	22 (12)
4. Increase in Engine Plus Nozzle/ Reverser Weight (2%)	33 (18) on mission	
5. Decrease in Coannular Noise Benefit (4 dB)	474 (256) on mission	

4.2.3 Lockheed Integration Study

The primary objective of the Lockheed study was to provide refined installation definitions and design validation for the VSCE-516 in the Lockheed CL-1607 supersonic cruise vehicle. The study was divided into four major areas: propulsion (including inlet selection and analysis), nacelle configuration comparisons, detail design configuration and technology projections.

The CL-1607 aircraft configuration is designed to cruise at Mach 2.55 on a hot day, STD +8°C (14.4°F). It has an over/under nacelle arrangement which is an attractive alternative to a four-engine under-wing arrangement used in previous Lockheed studies. Figure 4.2-17 shows that this baseline aircraft with VSCE-516 engines is constrained from achieving maximum range (center of knot-hole) by approach speed and sideline noise level.

4.2.3.1 Propulsion

Based on an assessment of all the candidate VCE concepts, the Mach 2.62 VSCE-516 was selected by Lockheed for the integration study. This engine is a higher Mach number version of the VSCE-502B. Previous Lockheed systems studies determined that 272 kg/sec (600 lbm/sec) was the size required for the VSCE-516 in the CL-1607 aircraft.

A parametric study of the influence of major inlet design parameters on supersonic cruise range and on transonic and take-off airflow matching was conducted to select an inlet for the VSCE-516. From this study, an axisymmetric inlet having a 76% internal contraction ratio and a translating centerbody was selected.

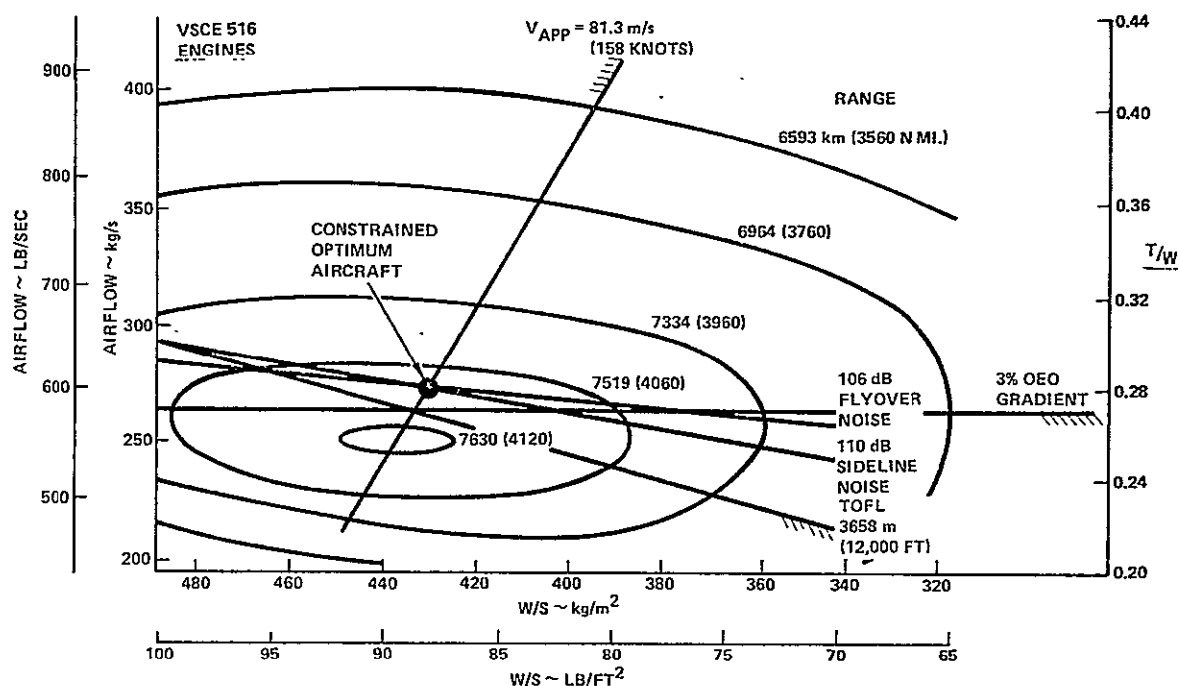


Figure 4.2-17 Matrix of Thrust to Weight and Wing Loading Ratios for the CL 1607 Aircraft With VSCE-516 Engines

An internal contraction ratio of 30% was found to be optimum for supersonic cruise but transonic-flow requirements dictated a higher contraction ratio, and 76% was chosen. This resulted in a range loss of about 1½% of total aircraft range. Take-off performance, however, improves at higher contraction ratios, especially at typical auxiliary door area to throat area ratios of 0.4 to 0.6. The relatively small range loss is acceptable in light of the transonic and take-off performance improvements.

Inlet study ground rules include a 10 degree initial cone half angle, a 5 degree inlet lip thickness angle, and a design Mach number of 2.75, corresponding to the local Mach number of the over-wing inlet. The under-wing inlet, whose local Mach number is 2.51, operates below inlet design Mach number, and is geometrically and aerodynamically similar to the over-wing inlet. Capture area was sized at cruise as a function of inlet local Mach number and engine airflow, so the under-wing inlet is smaller than the over-wing inlet.

The propulsion system installation losses which are accounted for in analyzing a supersonic engine and inlet configuration are inlet recovery, compressor bleed, accessory power extraction, nozzle performance, nacelle aerodynamic drag, inlet spillage drag, bypass drag, inlet bleed drag, and boattail drag. Nacelle aerodynamic drag, except for nozzle surface drag, is included in the aircraft drag polar, while all other losses are included in installed engine performance. Examples of installed subsonic and supersonic engine performance for the VSCE-516 are presented in Figure 4.2-18. These data are for the 272 kg/sec (600 lbfm/sec) version of the engine.

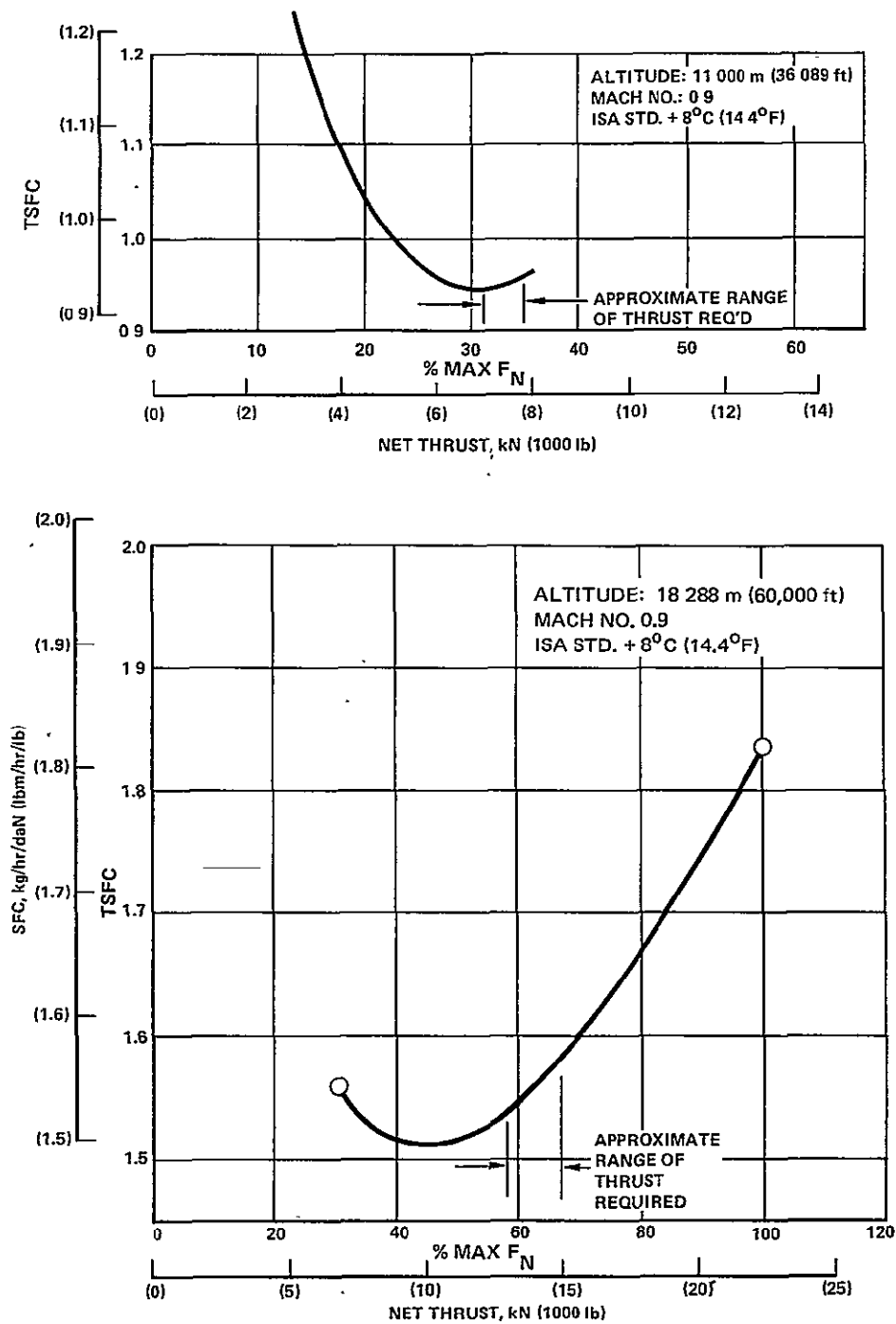


Figure 4.2-18 VSCE-516 Installed Fuel Consumption

4.2.3.2 Nacelle Configuration Comparisons

Analytical and design studies were conducted to evaluate two promising alternates to the geometrically similar over /under-wing axisymmetric inlet (referred to as the “uncompromised” design). These alternate concepts were: a two-dimensional, vertical-wedge design, referred to as the two-dimensional concept, and an axisymmetric inlet with maximum structural commonality designed into the under/over-wing inlets, referred to as the common structure inlet.

Because of the wasp-waist design of the VSCE-516, and the small size of the advanced accessories, no nacelle aerodynamic compromises were required to put all engine and airframe accessories within the nacelle contours. This feature is applicable to alternate configurations, since all nacelle concepts are similar in shape aft of the engine front face.

The two-dimensional concept was investigated to determine whether the increased transonic airflow capability of this type of inlet could improve the performance of the engine. Only small airflow increases, however, were available within mechanical limits of the engine rotors, so the performance improvement was also small. Since the two-dimensional inlet caused a 816 kg (1800 lbm) weight increase and climb performance has relatively little influence on mission range, this concept was not studied further.

The common structure inlet with under/over-wing nacelles structurally similar, except for the outer cowl forward of the throat which was modified to provide the required capture area, was evaluated. The final design of this configuration was similar to the “uncompromised” design (discussed in Section 4.2.3.3), but differed in several details (greater cowl lip angle under-wing, slight misalignment with local flow field, nozzle spacing increase) that decreased performance. Since poorer performance relative to the uncompromised design was obvious by inspection, study of this design was dropped.

An aerodynamic comparison was made between the “uncompromised” nacelle resulting from this study and the revised baseline nacelle from the systems studied in Task VI. Nacelle shapes for baseline and uncompromised designs are compared in Figure 4.2-19. The uncompromised nacelle inlet has been lengthened to accommodate internal centerbody support struts and to provide for better placement of blow-in doors. It has also been thinned down to a total structural angle at the lip of about 5 degrees, which results in an external cowl lip angle of about 1 degree. A drag comparison between the baseline and uncompromised design (Table 4.2-XII) shows that the uncompromised design offers the lower drag.

An aircraft weight comparison between baseline and uncompromised configurations is presented in Table 4.2-XIII. The increased length of the uncompromised nacelle design increases aircraft weight by 381 kg (839 lbm). Increases in nacelle/engine support structures add 96 kg (211 lbm) while increased wing bending relief results in a 41 kg (90 lbm) reduction in wing weight. Total weight increase due to the uncompromised nacelle concept is 424 kg (934 lbm) for all factors.

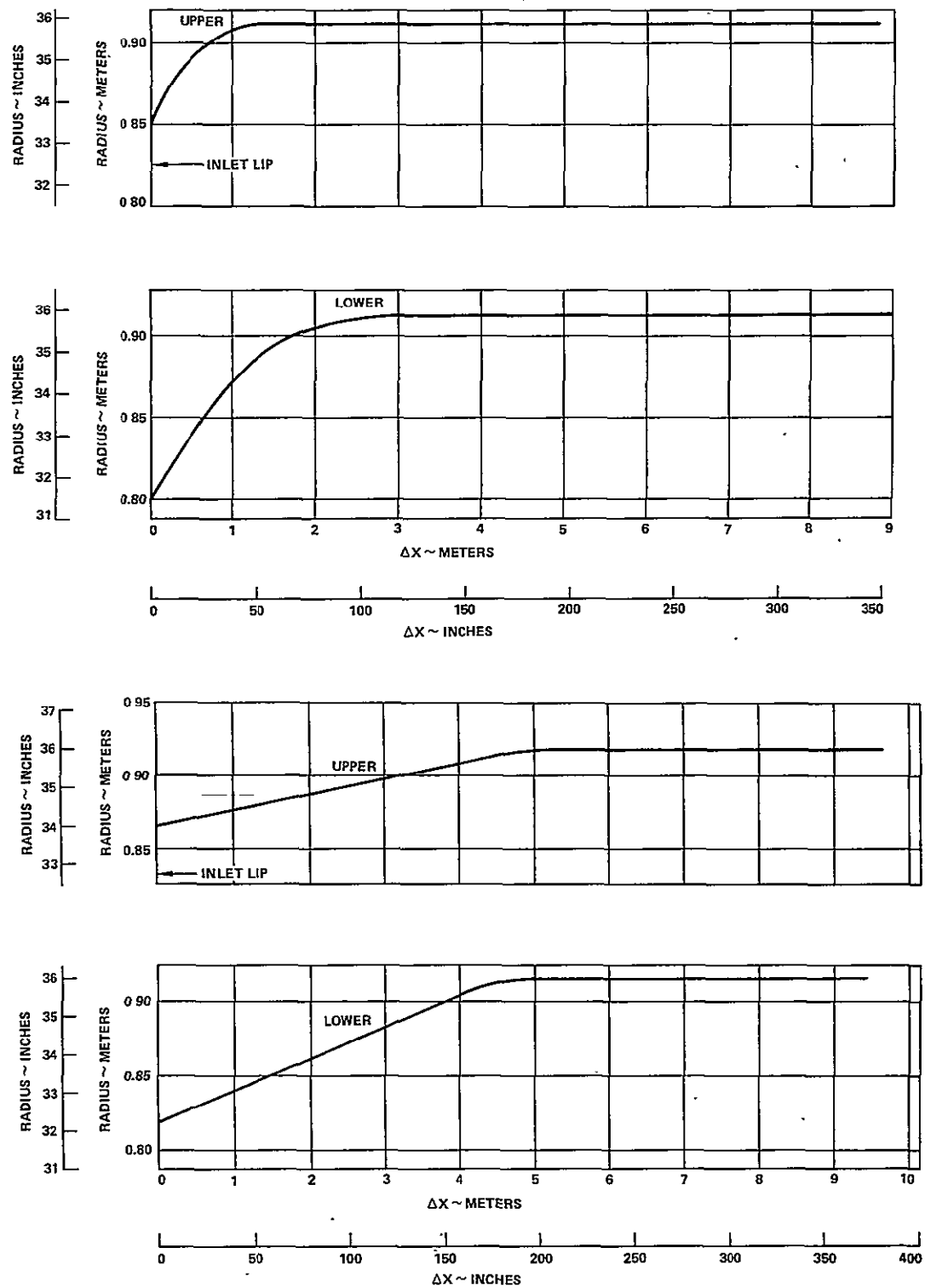


Figure 4.2-19 Baseline and Uncompromised Nacelle Shape Comparison

TABLE 4.2-XII

SYSTEM DRAG COMPARISON – TOTAL AIRCRAFT CONFIGURATION

	<u>Baseline</u>	<u>Uncompromised Configuration</u>
Mn = 2.55, h = 18,288 m (60,000 ft)		
$C_{D\text{MIN}}$	0.00789	0.00779
$(L/D)_{\text{MAX}}$	8.55	8.61
$\Delta C_{D\text{MIN}}$	—	–0.00010
Mn = 1.2, h = 12,192 m (40,000 ft)		
$C_{D\text{MIN}}$	0.01087	0.01070
$(L/D)_{\text{MAX}}$	10.46	10.56
$\Delta C_{D\text{MIN}}$	—	–0.00017

TABLE 4 2-XIII

WEIGHT STATEMENT

Item	Aircraft Configuration				Weight Change kg (lbm)		Reason for Change
	Baseline Weight kg (lbm)		Uncompromised Configuration Weight kg (lbm)				
Wing	24,605	(54,245)	24,564	(54,155)	−41	(−90)	Wing Bending Relief
Body	17,888	(39,437)	17,888	(39,437)			
Empennage	1,602	(3,531)	1,602	(3,531)			
Gear	10,970	(24,185)	10,970	(24,185)			Longer Inlets Engine Support Structure
Inlet	3,234	(7,129)	3,615	(7,968)	+381	(+839)	
Nacelle/Engine Support	1,631	(3,596)	1,727	(3,807)	+96	(+211)	
Engine (4)	16,014	(35,304)	16,014	(35,304)			Revised Fuel System
Propulsion Systems	2,380	(5,248)	2,376	(5,240)	−4	(−8)	
Systems	22,484	(49,569)	22,484	(49,569)			
Options	898	(1,980)	898	(1,980)			Revised Unusable Fuel
Standard/Operational	4,844	(10,679)	4,836	(10,661)	−8	(−18)	
Passenger/Baggage	26,308	(58,000)	26,308	(58,000)			
Zero Fuel Mass	132,858	(292,903)	133,282	(293,837)	+424	(+934)	

Aircraft mission performance was evaluated for baseline and uncompromised configurations. Take-off gross weight and payload was held constant at 268,530 kg (592,000 lbm) and 26,308 kg (58,000 lbm), respectively. The only factors affecting relative mission performance of the two configurations are the drag and weight differences discussed earlier. Engine performance is identical for both configurations. The net result of the drag reduction and weight increase of the uncompromised configuration is a 17 km (9 n. mi.) range advantage over the baseline (7510 vs. 7493 km) (4055 vs. 4046 n. mi.).

4.2.3.3 Detail Design Configuration

Figure 4.2-20 shows the VSCE-516 installation. Inlets are aligned with the local flow field at cruise while the engines are placed to conform to wing contour with the exhaust nozzle centerline set at 2.5 degrees down from horizontal.

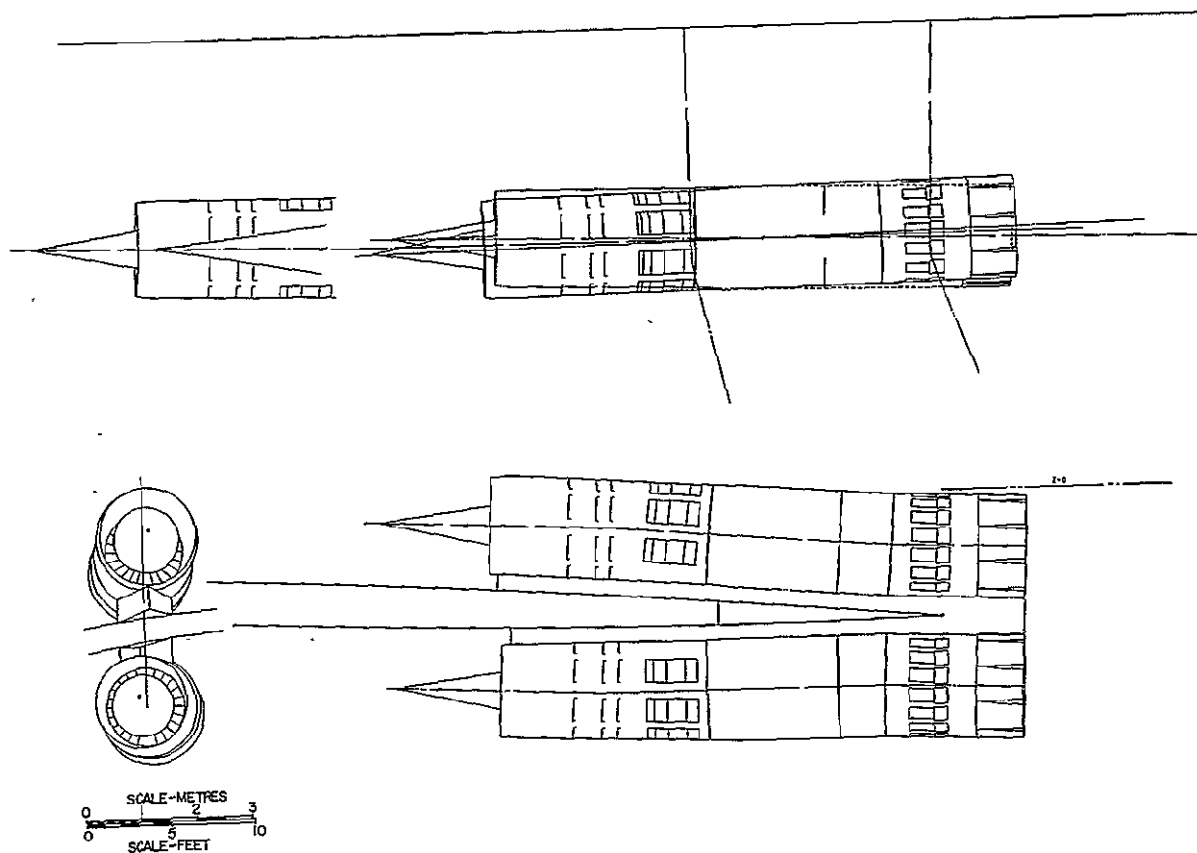


Figure 4.2-20 VSCE-516 Engine Installation

A full engine cutaway and section views of the VSCE-516 installation are shown in Figure 4.2-21. The engine is supported by two ball joint mounts at the forward fan case, 45 degrees on each side of vertical, which attach to the engine support beam with a second swivel joint

to allow outward movement due to fan case expansion. These front mounts take thrust, side, and vertical loads, while double vertical swivel links at the turbine case take vertical loads only.

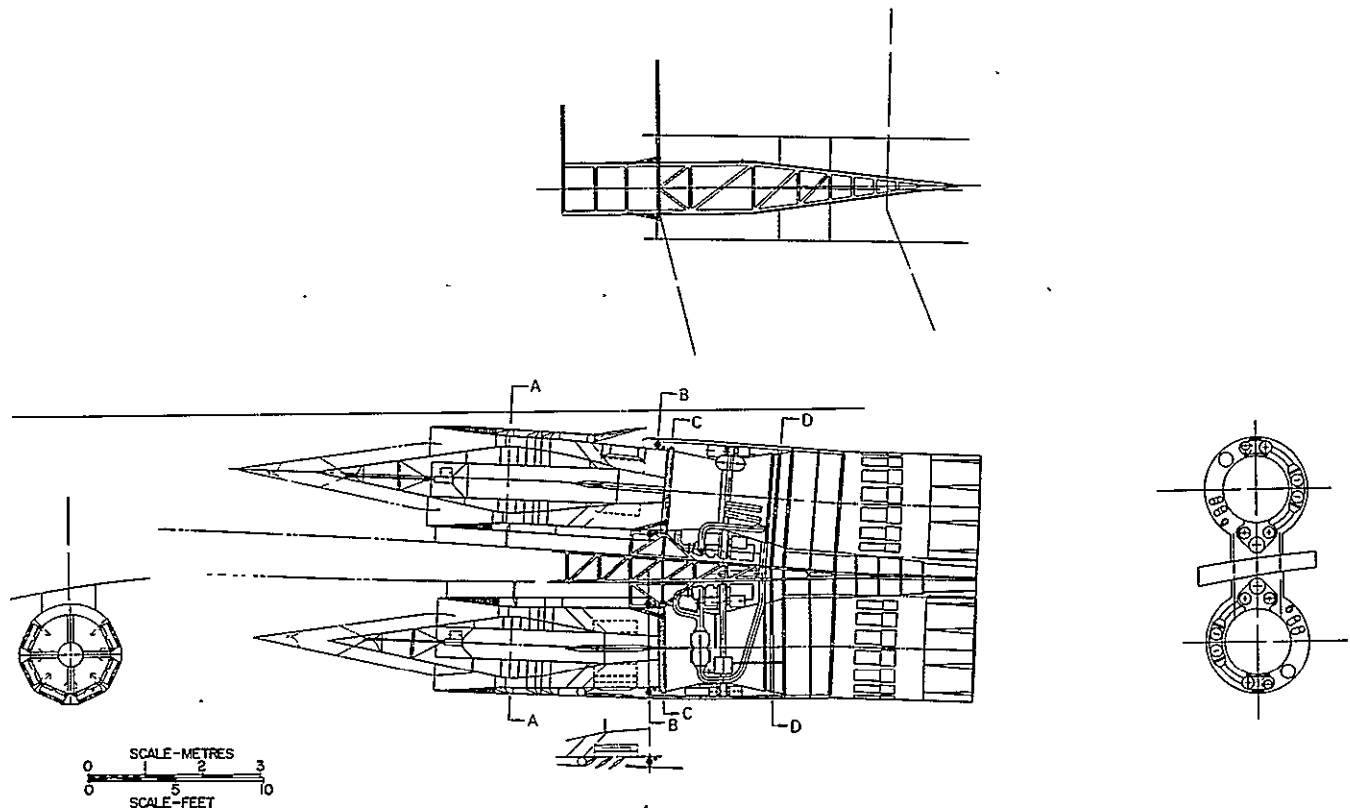


Figure 4.2-21 Cutaway of Axisymmetric Inlet and Nacelle

The translating centerbody of the inlet slides on a 3.05m (120 in) long, 0.533m (21 in) diameter tube which is supported by four hollow struts attached to the inlet outer cowl. These struts serve the dual purpose of transmitting centerbody loads to the outer cowl just forward of the firewall and allowing centerbody bleed to vent overboard.

Six auxiliary cowl doors, shown in Figure 4.2-22, are used to augment inlet airflow during take-off and low speed flight. These auxiliary doors are integrated with dynamically controlled bypass doors which are used for inlet terminal shock wave positioning and for airflow relief with an engine out.

An inlet bleed system is used to increase pressure recovery and stabilize inlet flow. Cowl bleed is exhausted through fixed nozzles on the cowl. Centerbody bleed is used for engine compartment ventilation at supersonic speeds, while at transonic and subsonic speeds ventilation is provided by auxiliary doors around the engine.

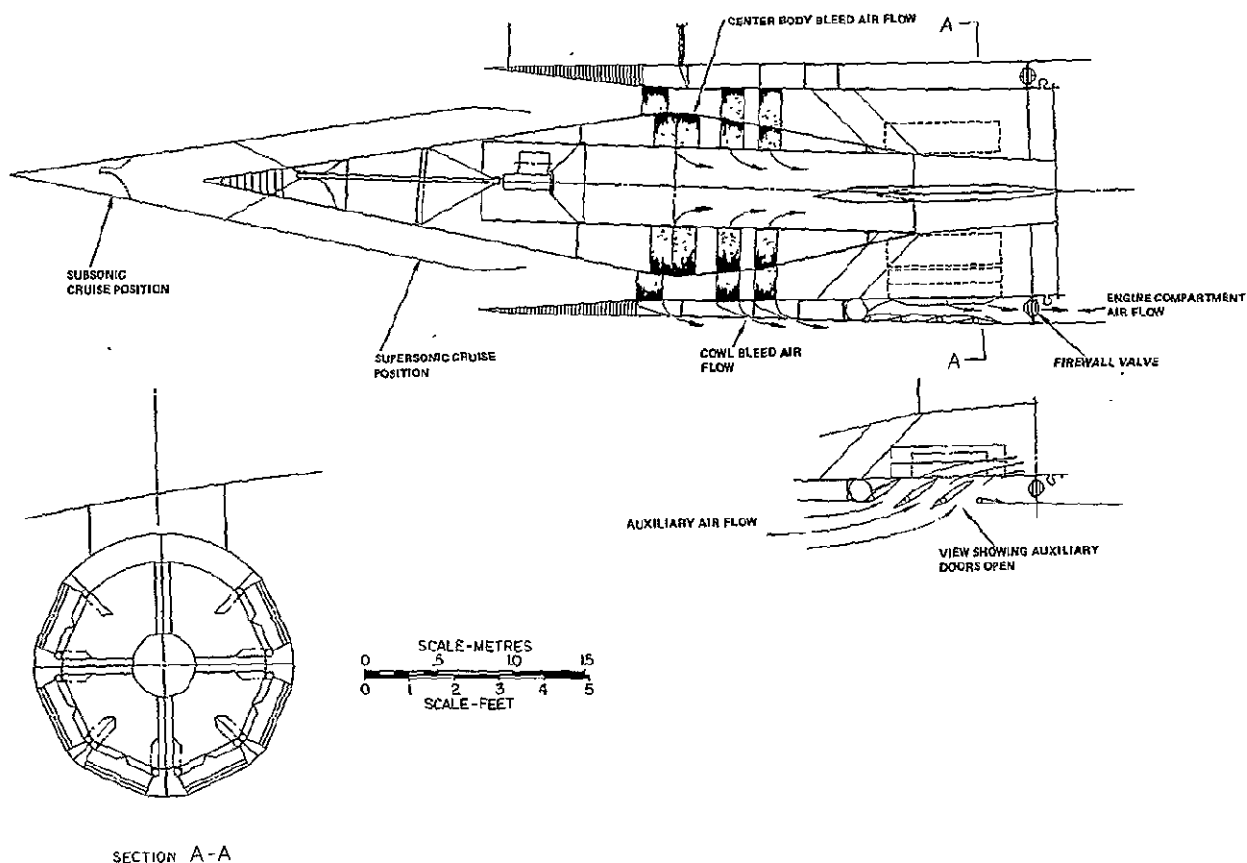


Figure 4.2-22 Auxiliary Inlet System

Inlet and nacelle structure is composed of titanium, titanium honeycomb, polyimide/graphite composite, and titanium-foam-polyimide/graphite sandwich. Approximately 40% of the inlet and nacelle is composed of composite materials, with titanium outer skins for foreign object impact and lightning strike resistance.

Advanced accessory state-of-the-art was assumed for the selected configuration. Two accessory gearboxes are used. One gearbox is used for driving the smaller engine accessories and is positioned within the nacelle on the side of the nacelle away from the wing. These accessories can be installed within a nacelle contour that doesn't exceed the maximum engine nozzle diameter, because of the wasp-waist shape of VSCE-516. A second gearbox is located on the opposite side of the engine within the pylon, driving the larger engine accessories as well as aircraft accessories.

To provide for shop maintenance, the inlet and engine assemblies may be removed independently of each other, as each has its own three-point quick-disconnect mount system. When either engine or inlet is removed independently of the other, a special tool is used to support the engine access door support beam, since this beam is attached to the inlet firewall.

Three alternate concepts for engine installation have been identified. The first method interchanges identical upper and lower gearboxes, as well as associated lines and equipment, so that the engine need not be inverted between upper and lower installations. No special internal lubrication system plumbing is required for this concept. This concept does require, however, different engine build-ups for upper and lower installations.

The second method is to invert the engines between upper and lower installations, requiring dual internal plumbing in the engine for the lubrication system, but reducing upper and lower engine build-up differences. A third concept provides a single PTO pad on the engine, with all accessories not required for engine operation located remotely and driven through shafting. These concepts, along with any new ones, will be evaluated in more depth during follow-on integration studies. All three concepts appear feasible and, it should be noted, none precludes the use of over/under engine location.

Results of an acoustic analysis of the VSCE-516 are shown in Table 4.2-XIV. The first column gives noise levels for fixed conditions which have been used throughout SCAR studies to compare engine noise. The data in the second column reflect flight conditions and noise levels for the baseline CL-1607-36 aircraft. Noise reductions for coannular effect are based on small model test data. Over/under engine effect noise reduction is also based on model tests, which showed a potential reduction of 5 dB. Since this effect hasn't been tested with coannular nozzles and the over/under configuration, only 3 dB reduction has been assumed.

One area of concern identified during the acoustic analysis is radiation of fan noise through the auxiliary inlet doors. High velocity airflows, with local Mach numbers of 0.7 to 0.9 in the inlet throat, should reduce noise emanation from the front of the inlet by 20 to 30 dB. However, since the auxiliary doors are open for take-off, fan noise emanating from them could be a problem. Noise reduction possibilities include premature closing of the doors, high velocity flow through the doors, and absorptive duct liners upstream of the fan, all of which will result in significant performance and/or weight penalties. The impact of this problem of auxiliary inlet noise needs further evaluation.

4.2.3.4 Technology Projections

The VSCE-516 engine definition is based on materials and component performance levels projected for a 1985 start of development. During this study, the sensitivity of aircraft mission performance to engine technology levels was investigated. As described in Section 4.3.2, P&WA estimated the effects of reduced component performance levels on the engine performance and weight. Lockheed estimated the maximum probable uncertainty of the projected performance levels. The changes in technology levels shown in Table 4.2-XV represent this estimate. These values were combined with the P&WA performance effects to obtain the TSFC effects shown. Using range sensitivity factors from Figure 4.2-23, the effect on mission range was predicted. The results are summarized in the last column of Table 4.2-XV.

Two parameters, nozzle coefficient and coannular noise relief, have a very significant effect on the range of the aircraft. A nozzle thrust coefficient reduction of 0.01 causes a loss in overall range of 300 km (162 n. mi.). A reduction in coannular noise benefit of 3 dB results in a 17 percent engine size increase, which reduces range by 319 km (197 n. mi.)

TABLE 4.2-XIV
ENGINE CYCLE NOISE ANALYSIS

	<u>Comparison Standard</u>	<u>CL 1607-36 Aircraft</u>
Thrust	197.5 kN (44,400 lbf)	183.8 kN (41,400 lbf)
Aircraft Mach No.	0.3	0.28
Flyover Altitude	550 m (1800 ft)	390 m (1280 ft)
Flyover Noise (EPNdB)	121.7	124.0
Annular Effect (EPNdB)	-8.8	-8.7
Over/Under Engine Effect (EPNdB)	-3.0	-3.0
Power Cutback (EPNdB)	-3.7	-6.4
Net Flyover Noise (EPNdB)	106.2	105.9
Sideline Maximum Noise Position		
Altitude	382 m (1250 ft)	382 m (1250 ft)
Sideline Distance	650 m (2128 ft)	650 m (2128 ft)
Sideline Noise (EPNdB)	118.9	118.6
Annular Effect (EPNdB)	-8.7	-8.7
Net Sideline Noise (EPNdB)	110.2	109.9
Traded FAR Part 36 Noise (EPNdB)	108.2	107.9

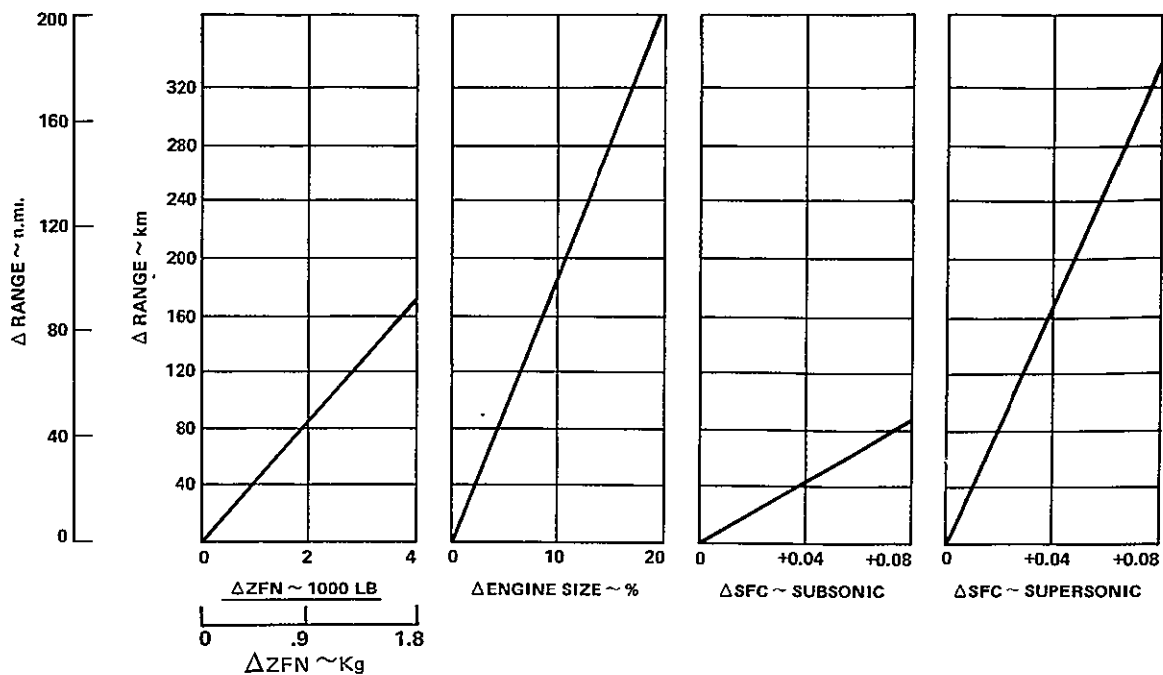


Figure 4.2-23 Range Sensitivity Factors – Lockheed Aircraft with VSCE-516 Engines

TABLE 4.2-XV

LOCKHEED RANGE SENSITIVITIES
VSCE-502B Technology Increments

Affected Item	Estimated Uncertainty Of Achieving Technology Level	Engine Performance Effect % Δ TSFC At Constant FN		Total Range Loss ~ km (n. mi.)
		Supersonic Cruise	Subsonic Cruise	
High pressure turbine efficiency	$-0.01 \eta_{\text{HPT}}$	+1.54	+1.18	126 (68)
Turbine cooling flow	$+0.015 W_{\text{AE}}$	+1.16	+0.89	93 (50)
Nozzle thrust coefficient	$-0.01 C_v$	+3.69	+1.78	300 (162)
Duct burner efficiency	$-0.015 \eta_{\text{DB}}$	+0.84	0.0	54 (29)
Coannular noise benefit	-3db	—	—	319 (172)
Engine weight	+2%	—	—	37 (20)

4.3 IMPACT OF TECHNOLOGY ON SELECTED ENGINES

Two methods were used to evaluate the impact of technology on the Variable Stream Control Engine (VSCE) and the rear-valve Variable Cycle Engine (VCE). The first method evaluated the effect of nearer term technology on engine performance, and on vehicle range and economics. This evaluation resulted in reoptimized engine cycles for the nearer term technology. The second method evaluated the sensitivity of engine and airplane performance to selected far term technology levels. This approach evaluated the effect of missed development goals for selected critical technologies. The cycles were not reoptimized in this sensitivity study.

The Variable Stream Control Engine was selected as the primary engine to study the impact of technology since it represents the most promising Variable Cycle Engine for powering an advanced commercial supersonic aircraft. The impact of technology on a rear-valve Variable Cycle Engine was also studied. This was done in order to determine if technology level and/or development confidence could alter the relative position of the two engines with respect to airplane range.

4.3.1 Technology Comparison

Promising VCE concepts which emerged from Phase II studies and underwent refinement during Phase III were based on advanced engine component and material technologies projected for engine certification in the early 1990's. To evaluate the impact of technology on engine performance, cycles comparable to those refined in Phase III were defined based on intermediate technology levels scheduled for demonstration about five years nearer than the technology used in the far term engine definition. The impact of this technology perturbation occurs primarily in the areas of high temperature material application, including the main and duct burners, and the high and low pressure turbines.

Burner liner materials projected for nearer term VCE applications have reduced metal temperature capabilities. For the main burner, this reduction limits the maximum allowable compressor discharge temperature, requiring adjustments to cycle overall pressure ratios. The duct burner liner will require increased quantities of cooling air. This higher cooling flow will increase the bypass stream losses associated with profile inefficiencies, reducing engine performance levels at each augmented flight condition.

Nearer term technology turbine airfoil and disk materials also show reductions in metal temperature capability. The problem of the disk is reduced with the lower cycle pressure ratios dictated by the main burner liner, but the airfoils require a decrease in combustor exit temperature along with small increases in turbine cooling air to maintain commercial life. Lowering the maximum cycle temperature while increasing cooling air requires a bypass ratio reduction to maintain the optimum jet velocity ratio between the primary and bypass stream for minimum noise at take-off and for maximum performance at subsonic and supersonic cruise. In addition to raising cooling flow levels, the material capabilities require reduced blade root stresses, which in turn require lower rotor speeds. These rotor speed reductions necessitate alterations to the compressor and turbine flowpath through either increased diameter or added stages to provide the design pressure ratio. This change will increase the

weight of the engine, in addition to the weight increase associated with the lower bypass ratio. The impacts of these technologies on the performance, weight and configuration of each of the prime VCE candidates are summarized in the following sections.

4.3.1.1 Nearer Term Technology VSCE

The VSCE concept is flexible enough to allow different levels of technology to be applied without altering the basic concept. Until this integration study, the VSCE concept had been defined only on the basis of advanced technology projections. This far term technology engine is identified as the VSCE-502B. The basic arrangement for the major engine components of the VSCE-502B is shown in Figure 4.1-1.

In order to assess the effect of nearer term technology on engine performance and weight, and vehicle performance, the nearer term technology described in Section 4.3.1 was incorporated in the VSCE-502B definition and the resultant cycle was designated VSCE-511. In addition to the technology change, the following ground rules were used in defining the VSCE-511 cycle.

- Fan pressure ratio is 3.3 (same as VSCE-502B) and bypass ratio was reduced to maintain the non-augmented exhaust velocity ratio of 1.0 at the sea level static take-off turbine temperature.
- The main burner throttle ratio, CET_{MCL}/CET_{TO} , is the same as the VSCE-502B (1.195).
- The overall pressure ratio is set to provide a maximum compressor discharge temperature of 620°C (1150°F) compared to 705°C (1300°F) for the VSCE-502B because of a reduction in hot section metal temperature capabilities.

Results of incorporating the new technology and applying the above ground rules to the VSCE-502B are shown in Table 4.3-I which compares the VSCE-511 to the VSCE-502B. The BPR for the VSCE-511 has been reduced from 1.3 to 0.85 and the OPR reduced from 20.0 to 13.5. The reduction in BPR resulted from the increased turbine cooling air (TCA) and reduced combustor exit temperature required by the nearer term technology. An overall pressure ratio for the VSCE-511 of 13.5 was established by the 620°C (1150°F) maximum compressor discharge temperature. A TSFC comparison between the VSCE-511 and VSCE-502B is shown in Figures 4.3-1 and 4.3-2 for subsonic and supersonic cruise, respectively. At subsonic cruise, the VSCE-511 is 9% poorer in TSFC than the VSCE-502B and supersonic cruise is 1.9% poorer at the required power settings.

In order to ensure that the VSCE-511 has the optimum cycle, several additional cycles were evaluated which represent small perturbations to the VSCE-511 cycle. These cycle perturbations are shown in Table 4.3-II and represent the following cycle changes relative to the VSCE-511.

- | | |
|------------------------------|---------------------------|
| ● Lower BPR | ● Lower FPR |
| ● Higher BPR | ● Lower FPR and lower OPR |
| ● Lower CET_{MCL}/CET_{TO} | |

TABLE 4.3-I

VARIABLE STREAM CONTROL ENGINE COMPARISON
Sea Level Static

	VSCE-511	VSCE-502B
Cycle characteristics		
Corrected airflow — kg/sec (lbm/sec)	408 (900)	408 (900)
Fan pressure ratio	3.3	3.3
Bypass ratio	0.85	1.3
Overall pressure ratio	13.4	20.0
Max. combustor exit temp — °C (°F)		
Primary burner	1370 (2500)	1480 (2700)
Duct burner	1425 (2600)	1425 (2600)
Engine weights and dimensions		
Engine + nozzle/reverser — kg (lbs)	6985 (15,400)(+ 15%)	6080 (13,400)
Max. diameter — m (in.)	2.24 (88)	2.24 (88)
Engine + nozzle/reverser length — m (in.)	7.26 (286)(+ 7.5%)	6.76 (266)

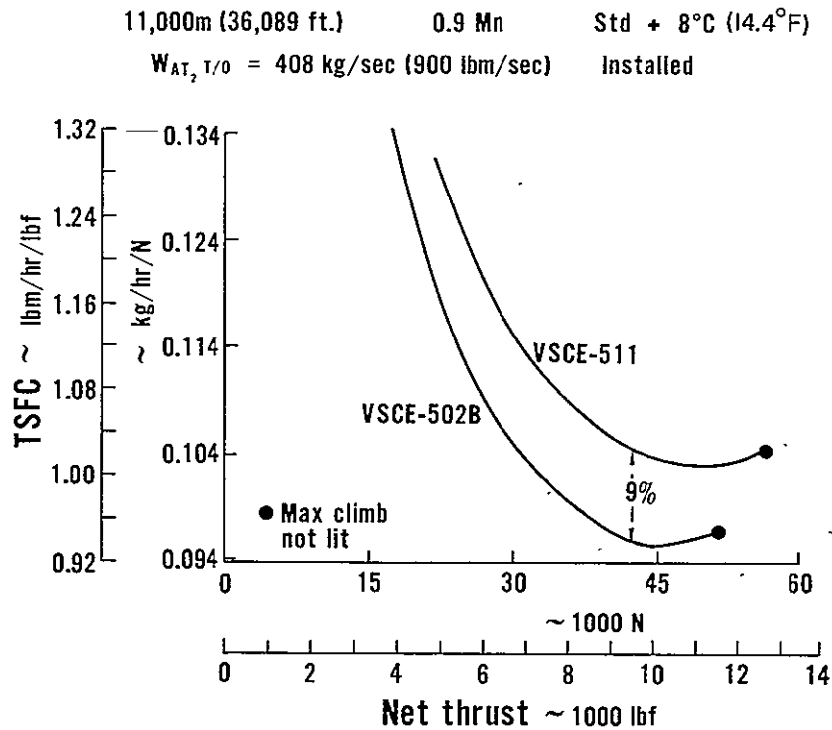


Figure 4.3-1 Subsonic Cruise Performance Comparison for VSCE-502B and VSCE-511 Concepts

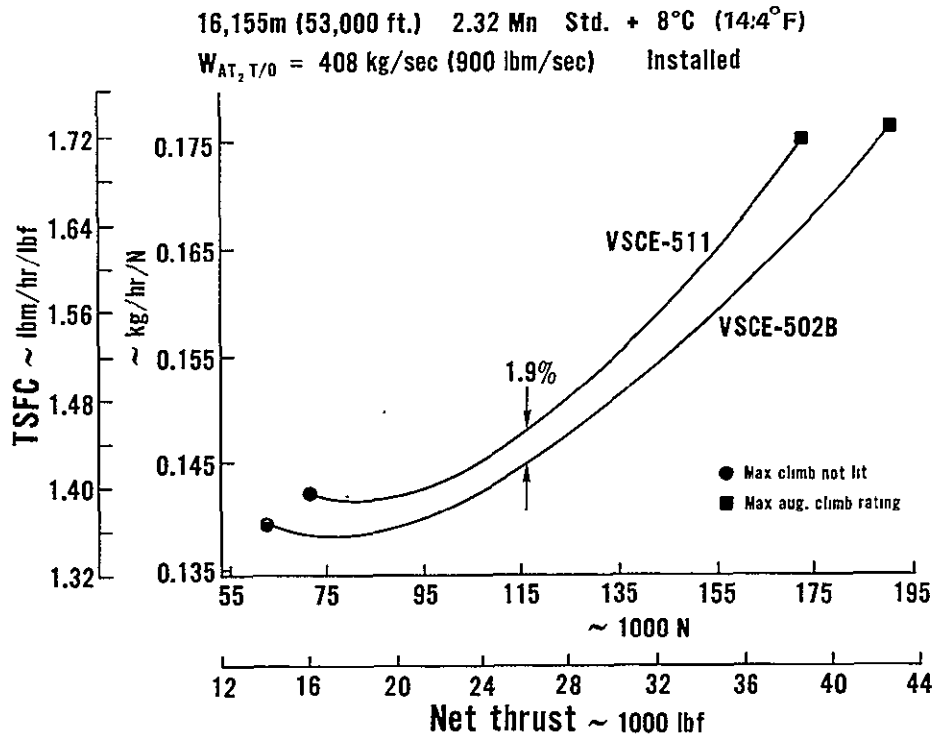


Figure 4.3-2 Supersonic Cruise Performance Comparison for VSCE-502B and VSCE-511 Concepts

TABLE 4.3-II

VSCE-511 CYCLE PERTURBATION TO ENSURE BEST SELECTION

Cycle	FPR	OPR	BPR	$\frac{V_{jd}}{V_{je}}$	$\frac{CET_{MCL}}{CET_{TO}}$
VSCE-511	3.3	13.4	0.85	1.0	1.19
Decrease BPR			0.5	0.86	
Increase BPR			1.0	1.24	
Reduce $\frac{CET_{MCL}}{CET_{TO}}$			1.0	1.0	1.12
Reduce FPR	2.8		1.08		1.19
Reduce FPR and OPR	2.8	11.7	1.10		

The TSFC levels obtained from these cycles relative to the VSCE-511 are shown in Figure 4.3-3. Only the reduced BPR case resulted in a supersonic cruise TSFC improvement. However, the lower BPR would result in a significant engine weight increase relative to the VSCE-511. Parametric study results from Phase II showed that the weight increase for reduced BPR more than offset the improved supersonic TSFC and was not a good trade. All other cases result in poorer supersonic cruise TSFC and the improvement in subsonic TSFC is not enough to offset that loss. Therefore, the VSCE-511 represents the best balance between performance and weight for the nearer term technology level.

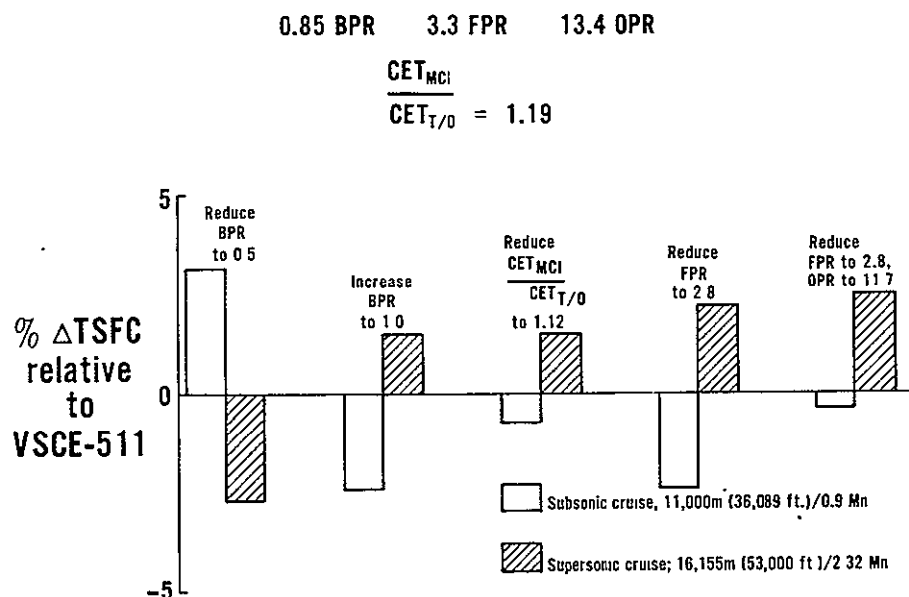


Figure 4.3-3 VSCE-511 Cycle Perturbation Results

In order to determine what technology changes had the greatest effect on the TSFC differences between the VSCE-511 and VSCE-502B, the cycle and component changes were made one at a time going from the VSCE-502B to the VSCE-511. The changes were made at the sea level static design point and each change was evaluated at the two flight conditions that are most critical to fuel consumption (subsonic and supersonic cruise). As each technology change was made, the BPR was adjusted to maintain the VSCE-502B nozzle jet velocity ratio.

The performance bookkeeping for the subsonic cruise flight condition (Figure 4.3-4) shows the hot section technology results in the largest increment in TSFC, 51% of the total. The reduction in CET and increase in TCA results in a 3.7% TSFC penalty and the high pressure turbine efficiency penalty, which is caused by the increased cooling air, is a 0.9% TSFC penalty. The other significant increase in TSFC is the result of reducing the OPR from 20.0 to 13.4 which gives a 3.2% increase in TSFC. The improvement in TSFC due to the nozzles is the result of a more favorable boattail angle for the VSCE-511.

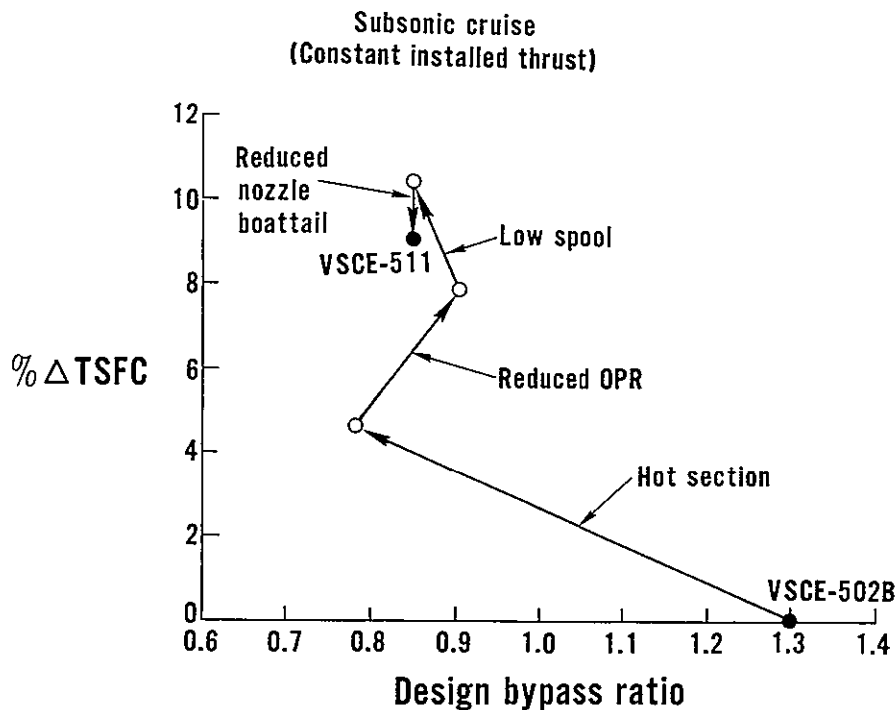


Figure 4.3-4 Effect of Nearer Term Technology on VSCE-502B Subsonic TSFC

At the supersonic cruise flight condition (Figure 4.3-5) the hot section technology again is shown to cause the largest increase in TSFC between the VSCE-502B and the VSCE-511. Increased TCA and reduced CET result in a 1.5% increase in TSFC. A 2.5 point reduction in duct burner efficiency is also a significant penalty at supersonic cruise. At this flight condition, the reduced OPR actually improves TSFC at a typical required thrust. This is the result of the increased duct burner fuel/air ratio required to offset the lower dry thrust of the higher OPR cycle.

Figures 4.3-4 and 4.3-5 also show the effect of nearer term technology on reducing the BPR of the cycle, which translates directly into engine weight because of the larger core size. Again, hot section technology results in the largest decrease in BPR. A flowpath comparison between the VSCE-511 and VSCE-502B is shown in Figure 4.3-6. Since the BPR is lower for the VSCE-511, the core flowpath is larger in both diameter and length, which results in a longer, heavier engine. An engine weight breakdown for the VSCE-511 and VSCE-502B is shown in Figure 4.3-7. Each element of the VSCE-511 contributes to the overall 15% weight increase over the VSCE-502B. However, the largest fraction of the 15% is shown to come from the larger high spool of the VSCE-511.

The increase in TSFC and engine weight of the VSCE-511 over the VSCE-502B was converted into a range comparison between the two cycles during the Phase IV airplane studies. These studies were conducted by P&WA, as well as by the airframe subcontractors, to aid in defining and evaluating nearer term technology engines. The airplane study methods and ground rules used by P&WA in Phase IV are similar to those of Phases II and III. The ground rules are reviewed in Table 4.3-III. A more detailed description is contained in the Phase II Final Report (Ref. 2).

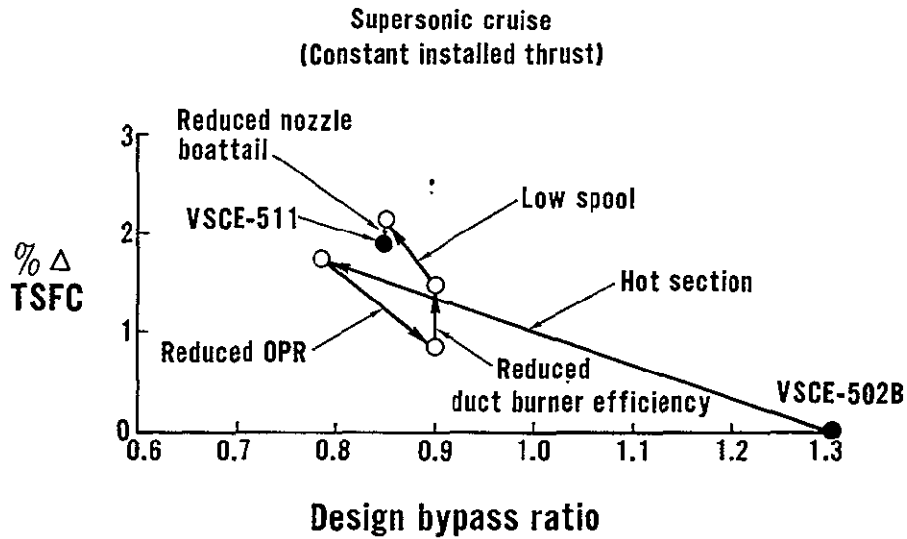


Figure 4.3-5 Effect of Nearer Term Technology on VSCE-502B Supersonic TSFC

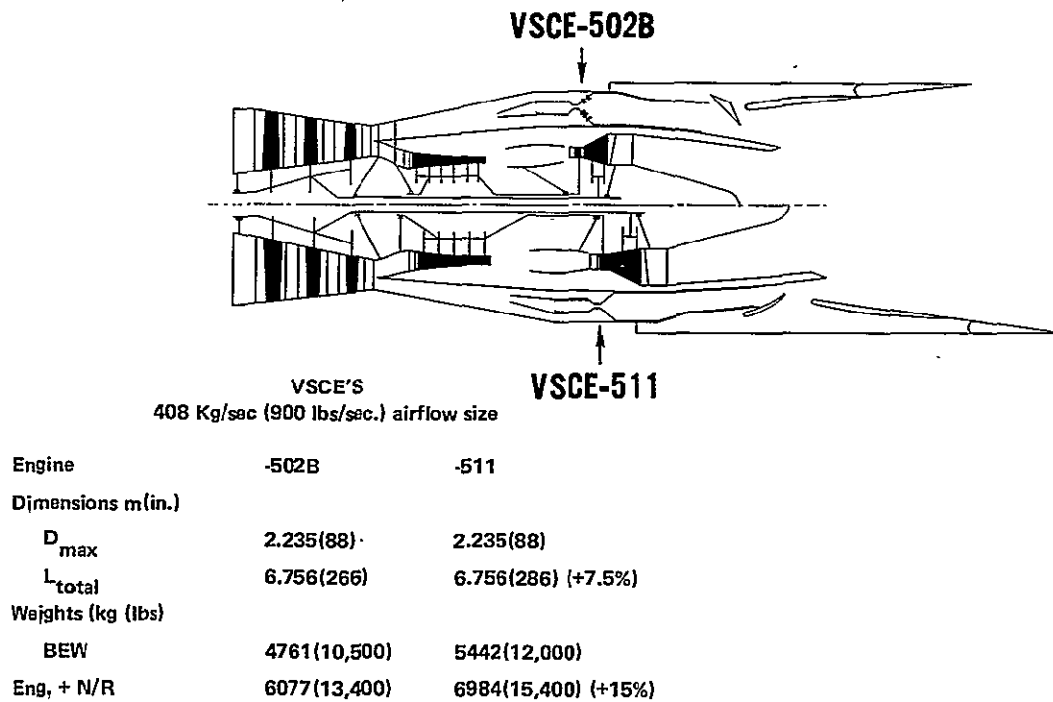


Figure 4.3-6 VSCE-502B and VSCE-511 Flowpath Comparison

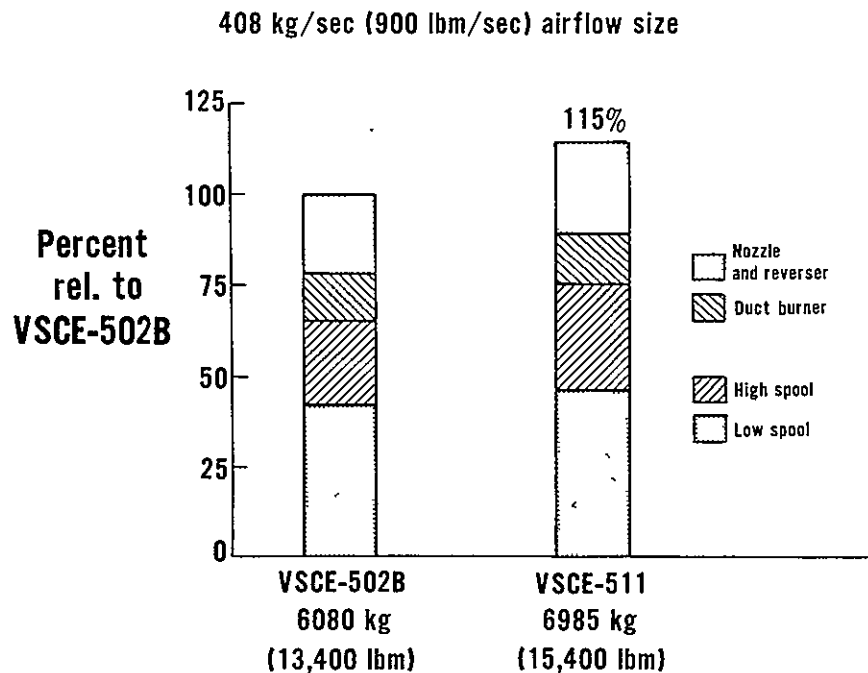


Figure 4.3-7 Engine Weight Breakdown

TABLE 4.3-III

P&WA AIRPLANE GROUND RULES

Airplane Design	— Modified Arrow Wing (NASA-CR-132374)
Flight Mach. No.	— 2.4
Thrust Loading	— 0.275
Payload	— 292 Passengers
TOGW	— 345640 kg (762000 lbm)
Range	— Variable
Fuel Reserves	— Lockheed Report LR 26133
Inlet	— Axisymmetric
Design Missions	— Nominal: All Supersonic
	— Alternate: Mixed with 110 km (600 n. mi.) initial subsonic cruise

The nearer term technology VSCE-511 was evaluated on both nominal and mixed missions. Figures 4.3-8 and 4.3-9 present a range comparison of the VSCE-511 with the far term technology VSCE-502B on both missions at constant 345640 kg (762,000 lbm) take-off gross weight. An influence coefficient evaluation of the causes of the range deficit of the VSCE-511 relative to the VSCE-502B showed that on the nominal mission about 25% is due to increased supersonic TSFC, 29% to subsonic TSFC, and 46% to engine weight. On the mixed mission, which is more sensitive to subsonic performance, 19% of the range loss is attributable to the supersonic TSFC increase, 40% to subsonic TSFC, and 41% to engine weight. The engine sizes required to meet FAR Part 36 and FAR Part 36 minus 5 EPNdB peak sideline noise levels are similar for VSCE-511 and VSCE-502B, as shown in Figures 4.3-8 and 4.3-9.

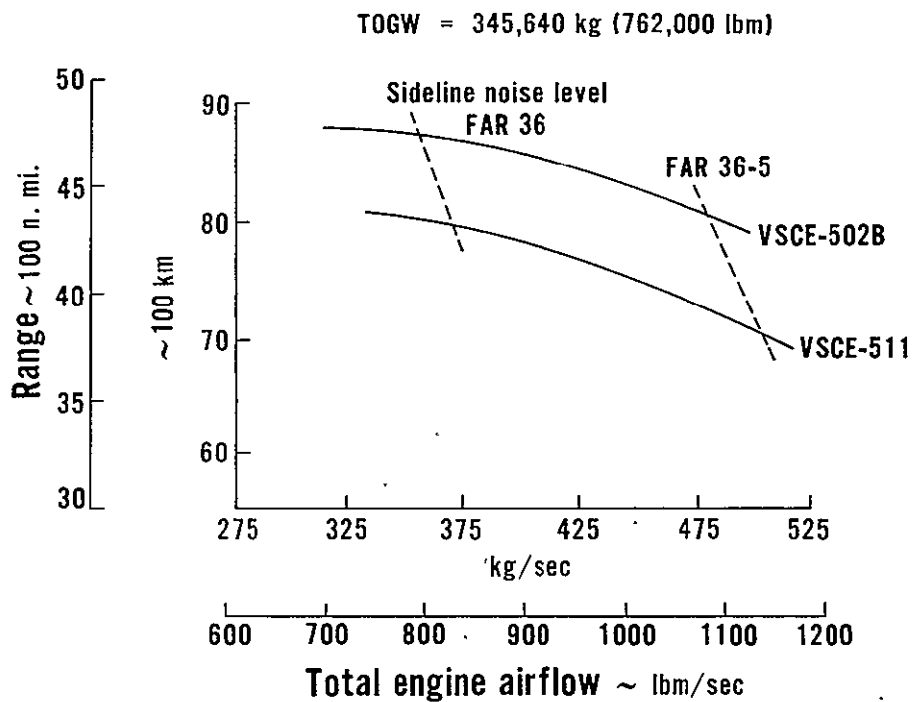


Figure 4.3-8 VSCE-502B/VSCE-511 Nominal Mission Comparison

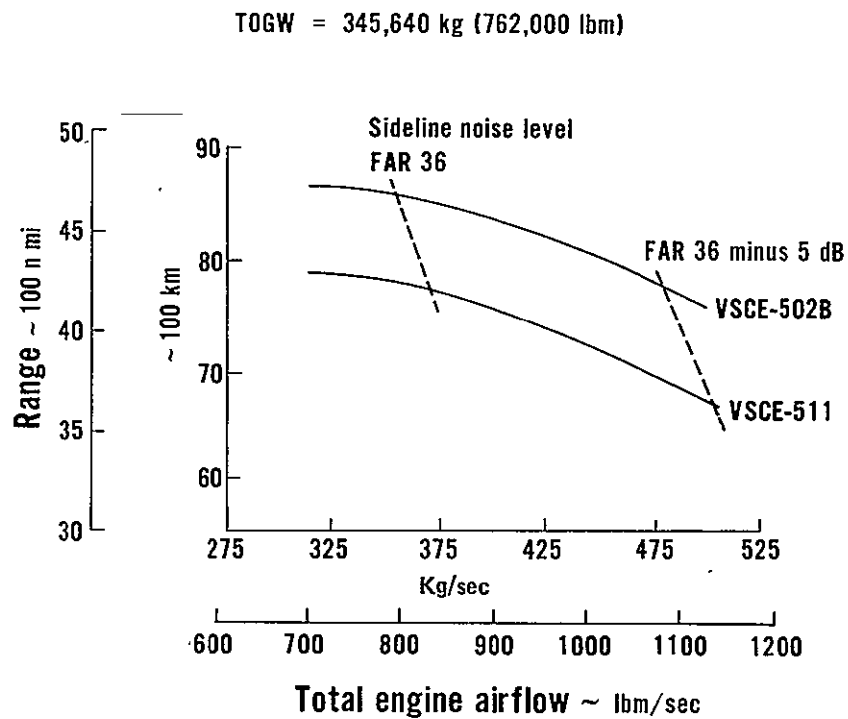


Figure 4.3-9 VSCE-502B/VSCE-511 Mixed Mission Comparison

4.3.1.2 Nearer Term Technology Rear-Valve VCE

The rear-valve VCE concept is a twin spool configuration incorporating a flow inverting valve which provides the capability for this engine to operate in a turbofan mode for low and intermediate power or in a twin turbojet mode for maximum power. The low spool consists of a multistage variable geometry fan driven by two low pressure turbines separated by a flow inverting/mixing valve. The high spool components and burner systems are similar to those in the VSCE. The rear-valve VCE concept based on far term technology consistent with the VSCE-502B is designated VCE-112C and the basic arrangement of this engine is shown in Figure 4.3-10.

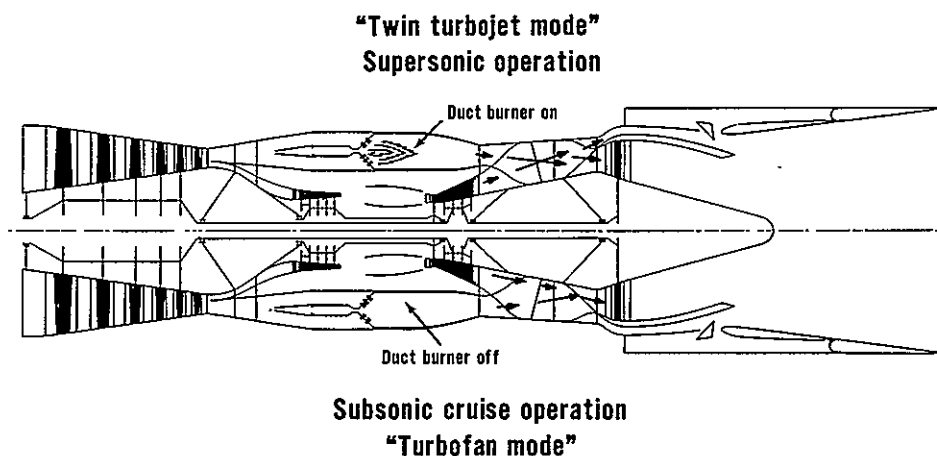


Figure 4.3-10 Basic Arrangement of Rear-Valve VCE-112C Concept

Near term technology consistent with VSCE-511 and described in Section 4.3.1 was applied to the rear-valve VCE concept. The resulting engine is designated VCE-115. In defining the VCE-115 cycle, the following ground rules were observed in addition to the nearer term technology assumptions.

- BPR was held at the VCE-112C level of 2.5 in order to minimize weight increases. This was determined to be a good trade during the Phase III parametric refinement study.
- The OPR is set to provide a maximum compressor discharge temperature of 620°C (1150°F) for the VCE-112C.
- FPR was reduced from 5.8 to 4.5 in order to maintain the BPR. This is consistent with the reduced combustor exit temperature.
- The low pressure turbine work split, defined as the ratio of low pressure turbine work ahead of the inverter valve to total low pressure turbine work, was reoptimized for the nearer term technology.
- The fixed primary jet was reoptimized for nearer term technology.

The cycle trends which were obtained from the low pressure turbine (LPT) work split and primary jet area optimization are shown in Figures 4.3-11 through 4.3-14. Figure 4.3-11 shows that LPT work split and relative primary jet area must be varied together to hold the required 408 kg/sec (900 lbm/sec) airflow at subsonic cruise. The LPT work split and relative jet area are further restricted in order to maintain adequate fan surge margin, as shown in Figure 4.3-12. Reducing the level of LPT work split and relative primary jet area provides better subsonic and supersonic TSFC, as shown in Figures 4.3-13 and 4.3-14. However, the fan stall margin (Figure 4.3-12) becomes the limiting criterion for determining how much the LPT work split and jet area can be reduced. Based on these curves, both the LPT work split and primary jet area were reduced about 8% relative to the far term technology VCE-112C. Table 4.3-IV shows the results of incorporating the nearer term technology into a rear valve VCE with a comparison of the VCE-112C and the VCE-115.

$$W_{AT_2 T/O} = 408 \text{ kg/sec (900 lbm/sec)}$$

$$11,000 \text{ m (36,089 ft.)} \quad 0.9 \text{ Mn}$$

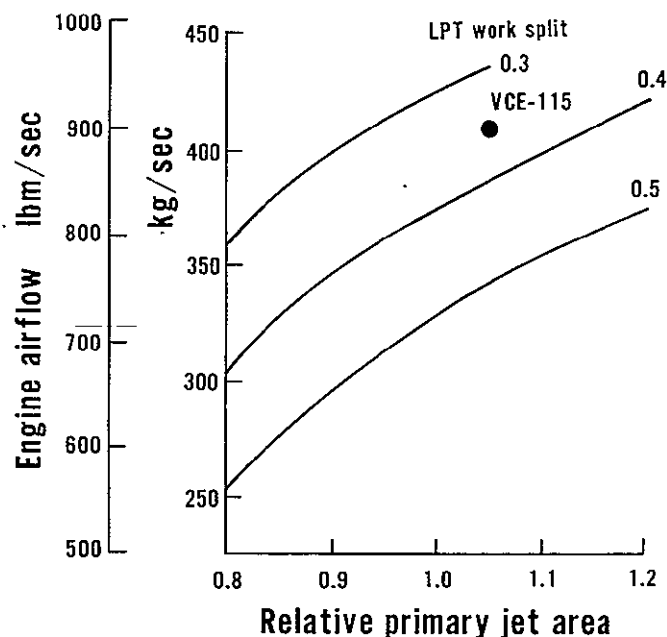


Figure 4.3-11 Rear-Valve VCE-115 Cycle Optimization, Subsonic Cruise Corrected Airflow

$W_{AT_2 T/0} = 408 \text{ kg/sec (900 lbm/sec)}$

11,000m (36,089 ft.) 0.9 Mn

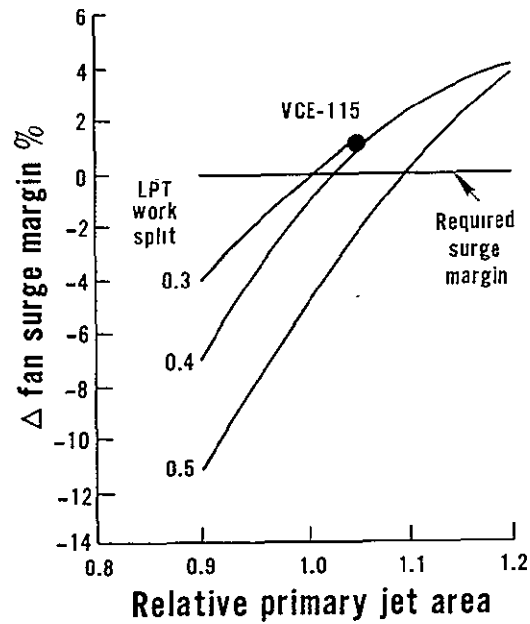


Figure 4.3-12 Rear-Valve VCE Cycle Optimization Δ Fan Surge Margin

$W_{AT_2 T/0} = 408 \text{ kg/sec (900 lbm/sec)}$

Uninstalled

11,000m (36,089 ft.)/0.9 Mn

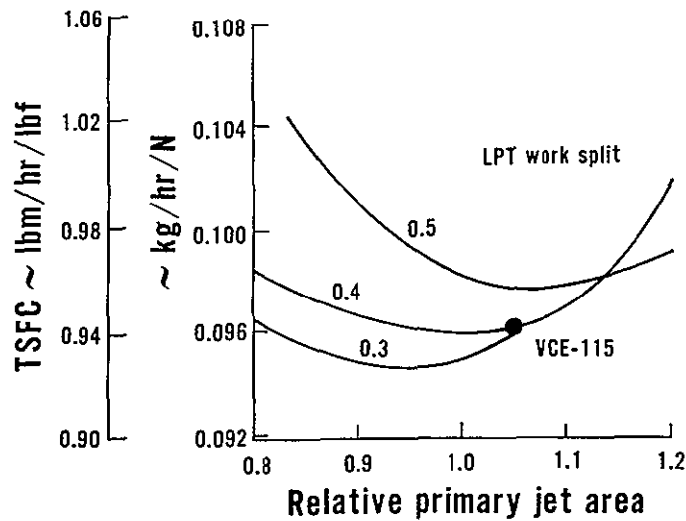


Figure 4.3-13 Rear-Valve VCE-115 Cycle Optimization, Subsonic Cruise

$$W_{AT_2 T/O} = 408 \text{ kg/sec (900 lbm/sec)}$$

Uninstalled

16,155m (53,000 ft.)/2.32 Mn

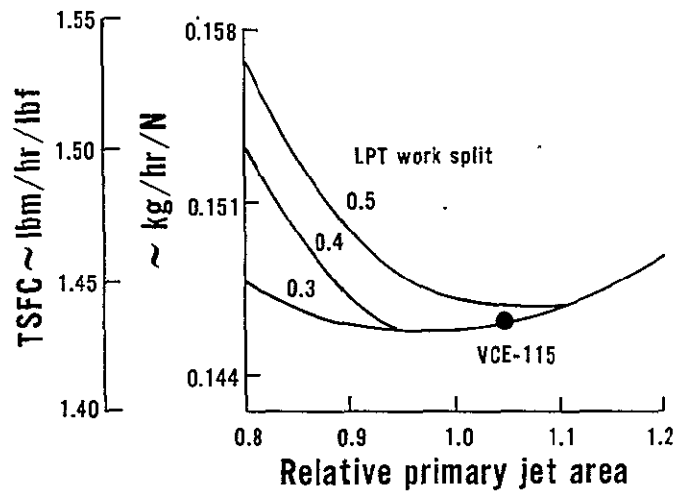


Figure 4.3-14 Rear-Valve VCE-115 Cycle Optimization, Supersonic Cruise

TABLE 4.3-IV

REAR-VALVE VCE CYCLE COMPARISON
Sea Level Static

	VCE-115	VCE-112C
Cycle Characteristics		
Corrected airflow — kg/sec (lbm/sec)	408 (900)	408 (900)
Fan pressure ratio	4.5	5.8
Bypass ratio	2.5	2.5
Overall pressure ratio	18.2	25.0
Max. combustor exit temp. — °C (°F)		
Primary burner	1425 (2600)	1540 (2800)
Duct burner	1040 (1900)	1040 (1900)
Low turbine work split		
$\left(\frac{\Delta H_{LPT1}}{\Delta H_{LPTtotal}} \right)$	0.37	0.40
Engine weights and dimensions		
Engine + nozzle/reverser — kg (lbm)	6670 (14,700)(+7.7%)	6190 (13,650)
Max. diameter — m (in)	2.25 (88.4)(+2.4%)	2.20 (86.3)
Engine + nozzle/reverser length — m (in)	8.85 (348)(+12.3%)	7.85 (310)

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The BPR has been held constant with the VCE-112C and the FPR reduced from 5.8 to 4.5 to adjust the cycles for the lower combustor exit temperatures. Overall pressure ratio was reduced from 25.0 to 18.2 in order to maintain the lower maximum compressor discharge temperature of 620°C (1150°F). The VCE-115 reflects an 8% lower LPT work split (Table 4.3-IV) and a reoptimized jet area. A TSFC comparison between the VCE-112C and VCE-115 is shown in Figures 4.3-15 and 4.3-16 for subsonic and supersonic cruise, respectively. At subsonic cruise, the VCE-115 is 1.8% poorer in TSFC than the VCE-112C and at supersonic cruise it is 3.6% poorer at the required power settings.

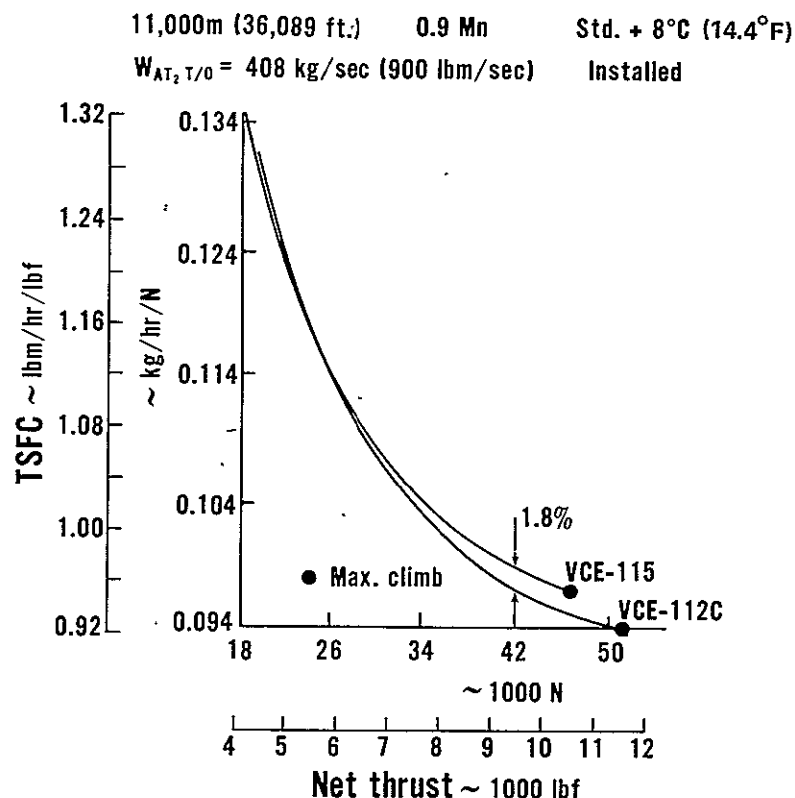


Figure 4.3-15 Rear-Valve VCE Subsonic Cruise Performance Comparison

Figure 4.3-17 shows the effect of technology on TSFC for both the VSCE and rear-valve VCE. The rear-valve VCE does not show as large a subsonic TSFC penalty for the nearer term technology as the VSCE because the reduced fan pressure ratio improved subsonic propulsive efficiency and minimized the TSFC increase. However, the opposite is true at supersonic cruise, and the reduced BPR of the VSCE-511 minimized the TSFC penalty and resulted in the nearer term VSCE having less of a TSFC penalty than the nearer term rear-valve VCE at the supersonic cruise conditions. A flowpath comparison of the VCE-112C and VCE-115 is shown in Figure 4.3-18. Since the fan pressure ratio in the VCE-115 is lower relative to the VCE-112C, the corrected flow leaving the fan is up, which results in larger flow areas and diameters through the core and nozzle. The large increase in engine length is largely due

to the longer diffuser between the fan and the duct burner, and to the increased nozzle flap length resulting from a constant maximum L/D ratio. A weight breakdown for the nearer and far term engines is given in Figure 4.3-19. As in the case of the VSCE, the nearer term rear-valve VCE weight increase of 10% relative to the VSCE-502B but is the cumulative effect of small changes to all the engine components. However, since the BPR was not changed in the VCE-115, the core and overall engine weight increases for the VCE-115 are not as great as the weight increase of the VSCE-511.

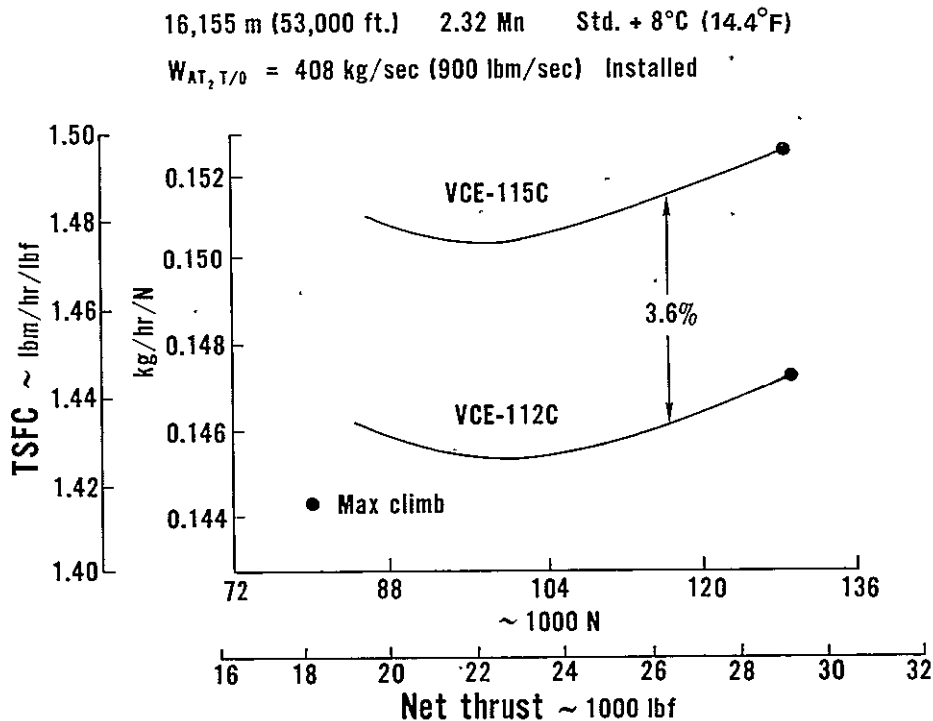


Figure 4.3-16 Rear-Valve VCE Supersonic Cruise Performance Comparison

The weight increase and TSFC increase of the VCE-115 relative to the VCE-112C was converted into a range comparison between the two engines. The same airplane ground rules used by P&WA for evaluating technology level for the VSCE's were used in the rear-valve VCE technology level evaluation.

Figures 4.3-20 and 4.3-21 show the effect of nearer term technology on aircraft range. VSCE-511 and VSCE-502B have been included to show that even though the range loss with nearer term technology is slightly less for the VCE case (-8.1% @ 360 kg/sec (800 lbf/sec) size vs -8.7% for VSCEs), the VSCE remains superior in range at both technology levels. On the nominal mission, 61% of the range loss of VCE-115 relative to VCE-112C is due to increased supersonic TSFC, 8% to subsonic TSFC and 31% to engine weight.

Std. + 8°C (14.4°F) Installed

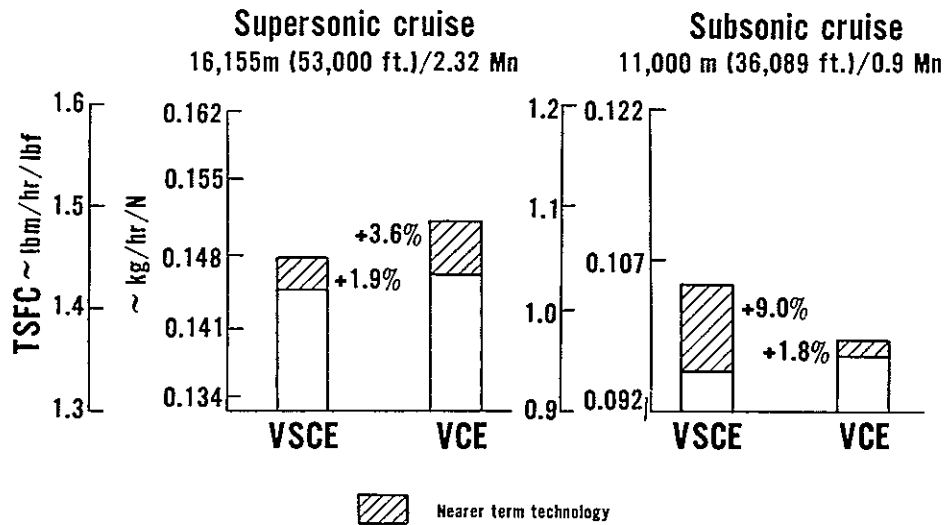


Figure 4.3-17 Effect of Technology on TSFC

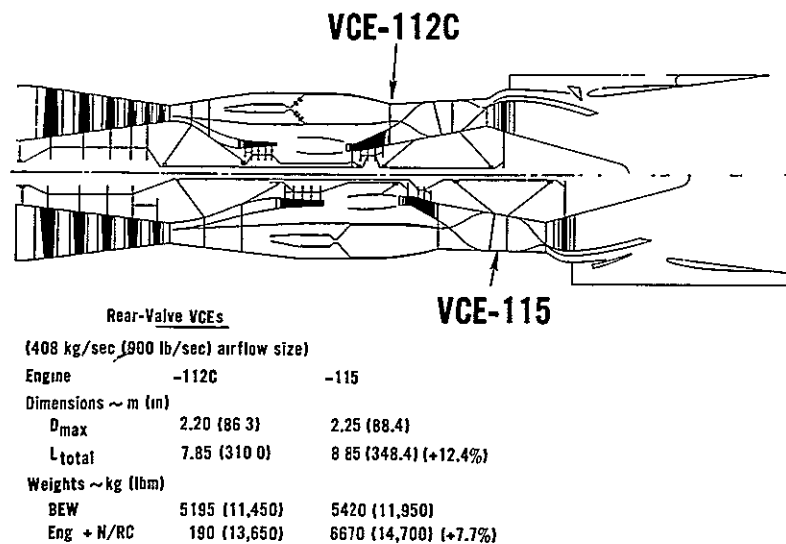


Figure 4.3-18 VCE-112C/VCE-115 Flowpath Comparison

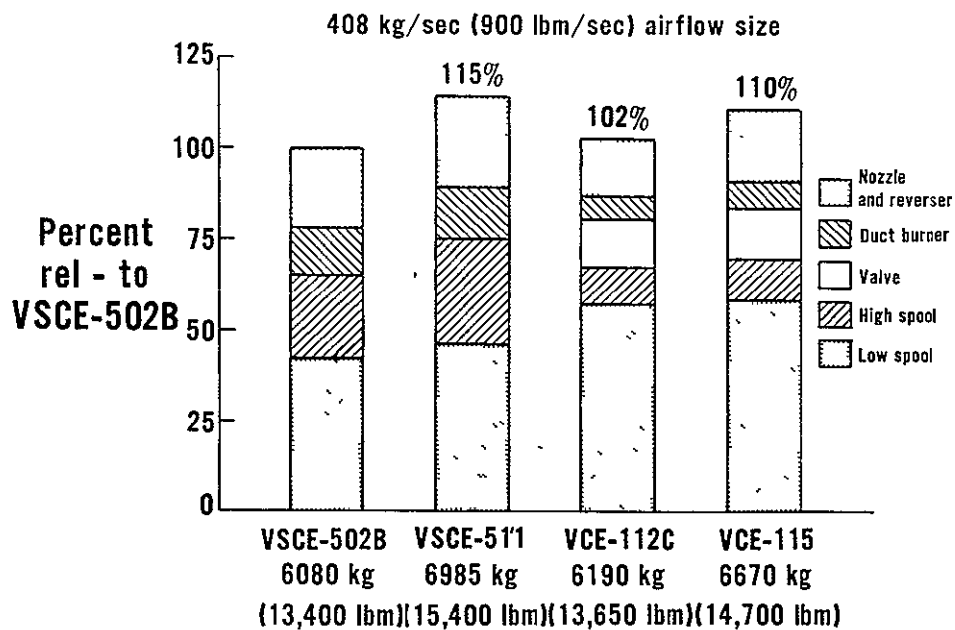


Figure 4.3-19 Effect of Technology on Engine Weight

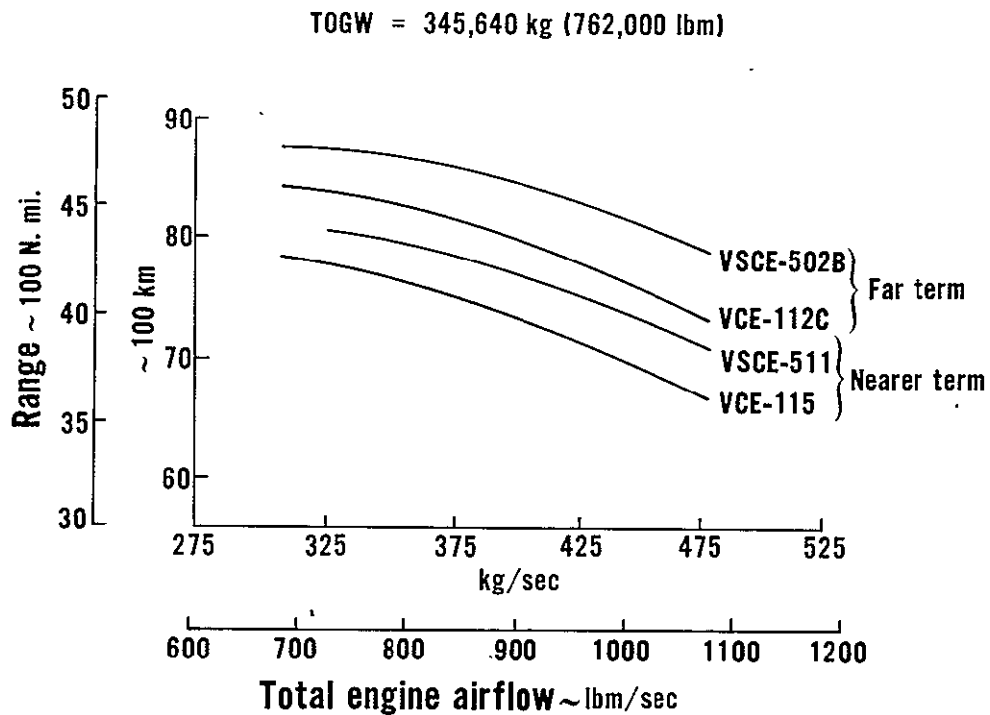


Figure 4.3-20 Nominal Mission Range Comparison

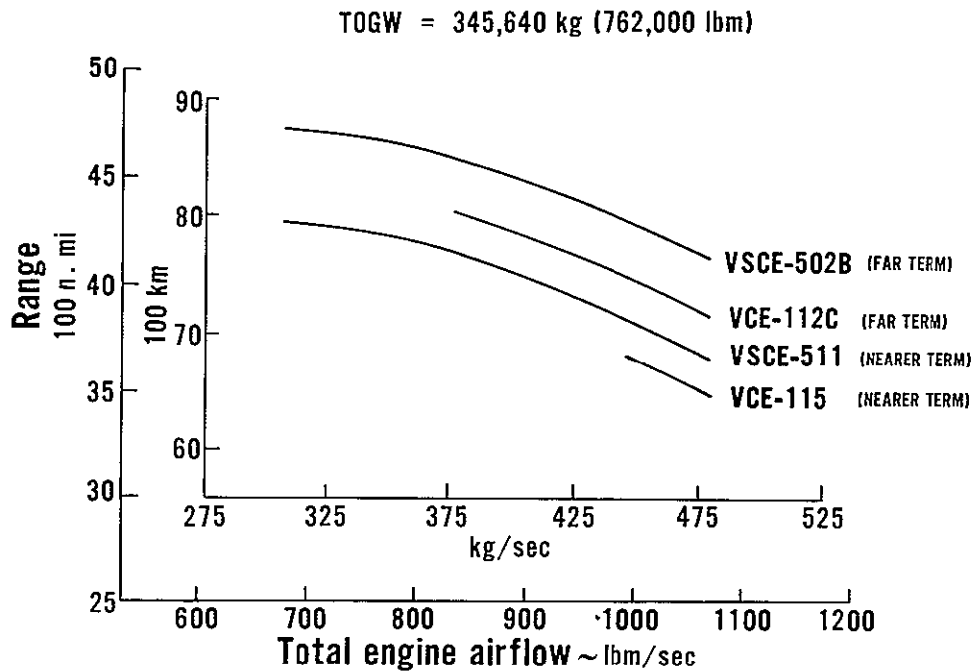


Figure 4.3-21 Mixed Mission Range Comparison

Both VCE-112C and VCE-115 have insufficient thrust in their turbofan mode to meet the initial subsonic cruise altitude requirement of 8380m (27,500 ft) on the mixed mission for smaller engine sizes. Instead of switching to the twin turbojet mode, which would provide sufficient thrust but penalize total range (much higher subsonic TSFC), the range curves are terminated where turbofan mode thrust becomes insufficient.

4.3.1.3 Comparison of Nearer Term Technology Evaluation Results

The application of nearer term technology has about equal overall impact on the VSCE and rear-valve VCE concepts. Since the relative position of these two engines with respect to airplane range was not changed by nearer term technology, the Variable Stream Control Engine remains the most promising concept for advanced supersonic commercial aircraft with either far or nearer term technology.

4.3.2 Technology Sensitivity Factors

4.3.2.1 Selection of Sensitivity Factors

The effect of not meeting certain engine critical technology projections was evaluated as a perturbation to selected engine and airplane mission performance. This approach for technology sensitivity evaluation is different from defining reoptimized cycles with nearer term technology discussed in Section 4.3.1. For this technology sensitivity evaluation, the cycles were not reoptimized for the missed technology goals. Instead, missed technology goals were handled by rematching the engine, but observing the limits of adjustment that are representative of an engine under development.

4.3.2.2 VSCE-502B and VCE-112C Technology Sensitivity

Specific areas of critical technology selected for the VSCE-502B are the high pressure turbine, the low emissions duct burner and the ejector/nozzle. Turbine materials have significant impact in that any deficit in projected temperature capability requires increased cooling air to maintain commercial life in the engine hot section. This cooling air not only affects the cycle, because of increased bleed from the primary stream, but also lowers the high pressure turbine efficiency. The bypass stream supplies almost twice the thrust of the primary stream at the supersonic cruise conditions, causing the thrust efficiency of the duct burner to have a significant effect on fuel consumption. The complexity of internal performance and nozzle performance has a drastic effect on the engine and airplane characteristics. In the case of the VCE-112C, the flow inverting valve was identified as critical technology in addition to those items identified for the VSCE-502B. The valve is a new component and is a key component of the rear-valve VCE. An increase in engine plus nozzle/reverser weight and a reduction in coannular noise benefit were also evaluated for both the VSCE-502B and VCE-112C. Table 4.3-V summarizes the critical technologies which were evaluated in this sensitivity study.

TABLE 4.3-V

SENSITIVITY EVALUATION OF CRITICAL TECHNOLOGY

Component Change	VSCE-502B	VCE-112C
Increase in turbine cooling air	X	X
+ 1% W_{ae} in 1st vane		
+ 1% W_{ae} in 1st blade		
-0.5% high pressure turbine efficiency		
1.0 point decrease in C_v	X	X
1.0 point decrease in duct burner efficiency	X	X
1.0% increase in valve pressure loss	NA	X
2.0 dB decrease in coannular noise benefit	X	X
2.0% increase in engine + nozzle/reverser wgt.	X	X

The increase in VSCE turbine cooling air (TCA) was evaluated using four methods of engine matching to determine which would be the most realistic approach to account for more conservative turbine materials during a development program. The four TCA cases were:

Case No. 1: First vane cooling flow was increased by 1% of engine core flow. First blade cooling flow was also increased by 1% of engine core flow. The HPT efficiency

was debited 0.5% for aerodynamic losses associated with increased cooling flow. The TCA was increased at constant turbine temperature and V_{jd}/V_{je} and flow areas were allowed to vary. This case simulates a resizing of engine areas to accommodate increased TCA.

Case No. 2: The TCA changes specified in Case No. 1 were incorporated off design and the flow areas were fixed. This case simulates deterioration in the form of excessive air.

Case No. 3: The TCA changes specified in Case No. 1 were made in the design point but BPR was dropped (0.07) to maintain a constant V_{jd}/V_{je} . This case simulates a resizing of engine areas and the ID to OD fan splitter plane areas to accommodate increased TCA.

Case No. 4: The TCA changes specified in Case No. 1 were made in the design point but CET_{TO} was increased 20°C (35°F) to maintain a constant V_{je}/V_{jd} . This case simulates a resizing of engine areas and a new throttle ratio to accommodate increased TCA.

The performance changes resulting from the four cases of rematching to accommodate TCA increases are shown in Table 4.3-VI. Case No. 1 was selected as the best method to represent an increase in VSCE-502B TCA since it minimizes the TSFC penalty and represents a hardware change that could be easily made during a development program. Case No. 3 actually resulted in the minimum supersonic TSFC penalty, but the hardware changes required to reposition the fan splitter would be more difficult to make late in a development program. Results of the TCA study on the VSCE also were applied to the rear-valve VCE.

TABLE 4.3-VI

SENSITIVITY EVALUATION OF CRITICAL TECHNOLOGY
Effect of Increased Turbine Cooling Air

Method of Cycle Rematch*	% Δ TSFC for VSCE-502B	
	11,000 m (36,089 ft.)/0.9 Mn	16,155m (53,000 ft.)/2.32 Mn
1. Hold CET, let V_{jd}/V_{je} increase, high and low pressure turbine areas adjusted for fixed operating lines	+0.59	+0.74
2. Hold CET, let V_{jd}/V_{je} increase, high and low pressure turbine areas fixed	+0.82	+0.97
3. Hold V_{jd}/V_{je} by reducing BPR	+0.99	+0.48
4. Hold V_{jd}/V_{je} by increasing CET	+0.61	+0.96

*Method no. 1 selected for sensitivity studies

In addition to the TCA increase, the VSCE-502B and VCE-112C were evaluated for changes in duct burner efficiency and nozzle velocity coefficient. The effect of valve pressure loss was evaluated in the VCE-112C. Figures 4.3-22 and 4.3-23 show the VSCE-502B and VCE-112C sensitivity to technology. For both engines, a reduction in nozzle velocity coefficient is shown to have the greatest impact on TSFC. The TSFC penalty for a 1.0 point reduction in duct burner efficiency is not as significant as might be expected since the duct burner fuel/air ratio at supersonic cruise is low (approximately 0.011).

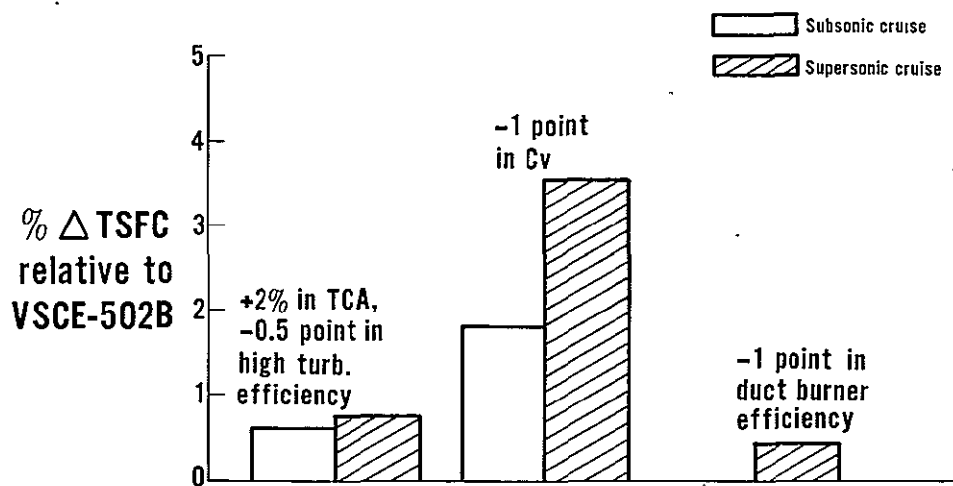


Figure 4.3-22 VSCE-502B TSFC Sensitivity to Technology

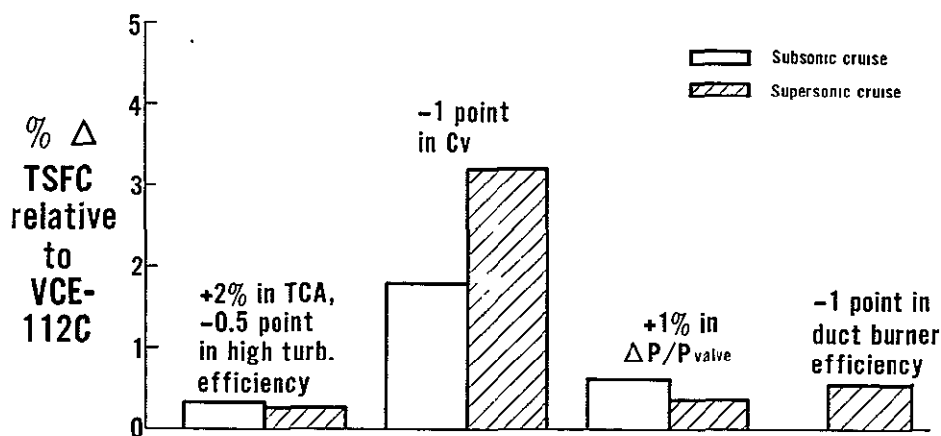


Figure 4.3-23 Rear-Valve VCE-112C TSFC Sensitivity to Technology

The P&WA analysis of the effect of critical technologies on airplane range for the nominal mission is shown in Figures 4.3-24 and 4.3-25 for the VSCE-502B and VCE-112C.

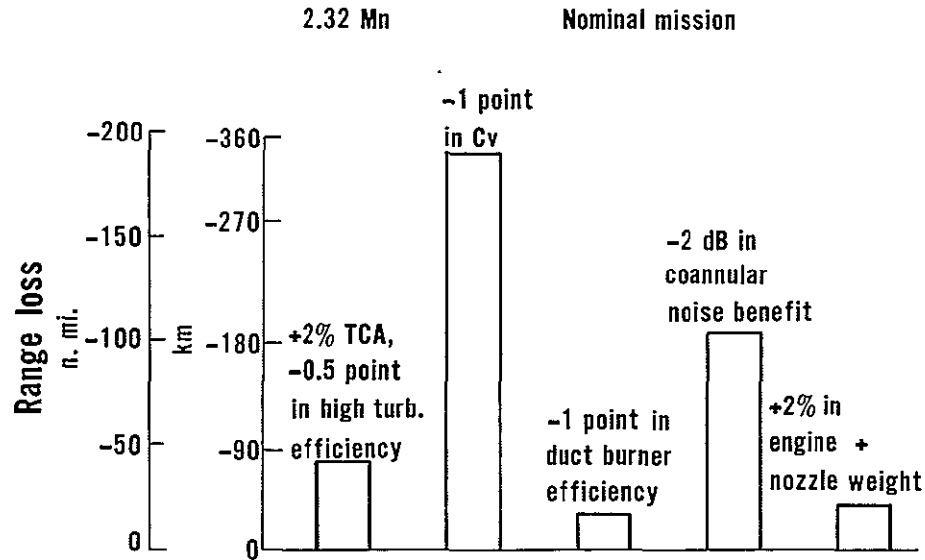


Figure 4.3-24 VSCE-502B Range Sensitivity to Technology

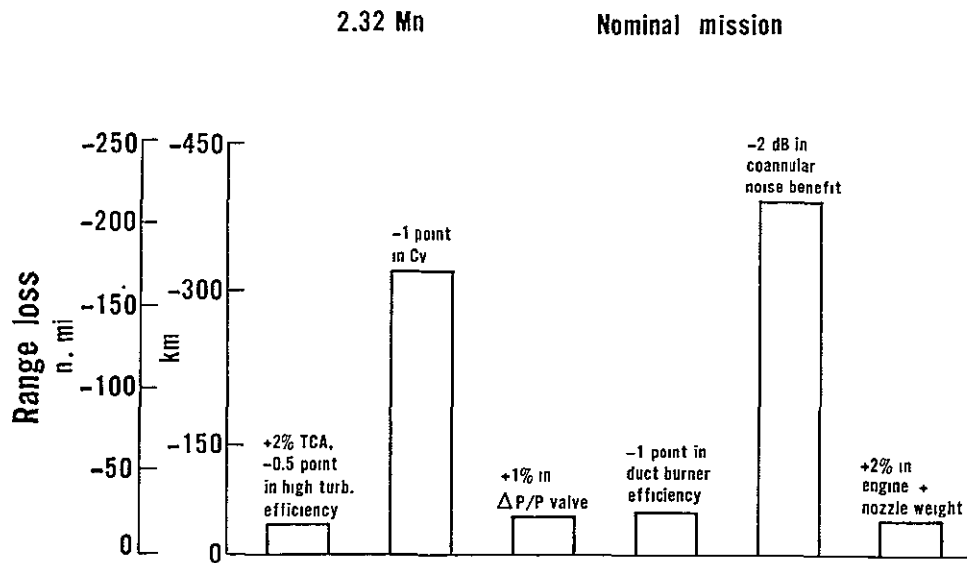


Figure 4.3-25 Rear-Valve VCE-112C Range Sensitivity to Technology

Again, nozzle velocity coefficient shows a very significant effect on range. The 2 dB reduction in coannular noise benefit also has a significant effect on range, especially for the VCE-112C.

In evaluating the reduction in coannular noise benefit, the engines were scaled up and throttled back to the required power setting. The rear-valve VCE was more sensitive to noise than the VSCE because it is a larger engine, and the increased size resulted in a sharper fall off in range than in the VSCE. Although the reduction in duct burner efficiency did not have a large effect on range, maintaining a high level of duct burner efficiency is very important in order to reduce emissions levels and provide an environmentally acceptable airplane.

4.3.2.3 Airplane Companies Evaluation of Technology Sensitivities

The impact of these technology perturbations on both subsonic and supersonic cruise TSFC was provided to Boeing, Douglas and Lockheed. The results of the technology sensitivity studies are summarized in Sections 4.2.1.5 (Boeing), 4.2.2.3 (Douglas) and 4.2.3.4 (Lockheed).

Based on these integration study results, research efforts should concentrate in the areas of exhaust nozzle performance and coannular noise verification. Hot section material and cooling technology must also be stressed. Research and experimental evaluation of advanced duct burners must also be conducted, with emphasis on performance, which is closely tied to exhaust emissions, to ensure environmental acceptability for the VSCE.

5.0 VCE TECHNOLOGY RECOMMENDATIONS

One of the primary objectives of the SCAR/AST Propulsion System Studies is to identify the engine related technologies that offer the greatest potential for improving the environmental and economic characteristics of advanced supersonic commercial transports.

Technology requirements and program recommendations have been reviewed and updated at the conclusion of each AST propulsion study phase. As the number of engine concepts has been reduced, the technology recommendations have been concentrated on the most promising concepts. The Variable Stream Control Engine (VSCE) was identified in Phase III as the most promising VCE concept and the technologies identified at the end of Phase III were based on the VSCE requirements. The Phase III technology requirements were not changed by the Phase IV study; rather, they were confirmed. However, the program recommendations have been reviewed and, where necessary, updated.

Critical technology requirements for the Variable Stream Control Engine are listed in Table 5-I. Recommendations for related programs for the technology areas listed in Table 5-I are discussed in Sections 5.1 to 5.7.

In order to continue the refinement of the VSCE into a system meeting commercial standards of safety, stability, reliability and maintainability, preliminary design and engine/airframe integration efforts are recommended in the areas shown in Table 5-II and discussed in Section 5.8 (VSCE Preliminary Design and System Integration).

TABLE 5-I

VCE CRITICAL TECHNOLOGY REQUIREMENTS

- * Low noise coannular nozzle
- * Low emissions duct-burner
- Variable geometry components
 - Fan
 - Compressor
 - Inlet
 - Nozzle
 - Nozzle/Ejector/Reverser System
- Low emissions primary burner
- Hot section technology
 - Advanced directionally solidified airfoil materials and coatings
 - Ceramic endwalls and tip seals
 - High creep strength disk material
 - Active tip clearance control system
 - High temperature burner liner material
- Full authority electronic control system
- Propulsion system integration

*Programs are in progress in these areas.

TABLE 5-II

RECOMMENDATIONS FOR JOINT ENGINE/AIRPLANE COMPANY INTEGRATION STUDIES

Preliminary design of inlet/engine

- Variable geometry requirements
- Performance
- BLC system
- Structural
- Mechanical
- Stability/distortion
- Noise control

Preliminary design of nozzle/reverser

- Reverser targeting and effectiveness
- Trade studies
- Mechanical
- Structural
- Acoustic treatment

Preliminary design of engine/airframe interface systems

- Secondary flow system
- Fuel/air thermal management
- Airframe accessories
- Integrated control system

Continue evaluation of programmed throttle schedule for noise abatement

A VCE components testbed program is in progress (NAS3-20048) with objectives of demonstrating duct burner performance and coannular nozzle noise benefits using a large scale engine to simulate VSCE conditions. This program and the VCE Experimental Program are discussed in Section 5.9.

5.1 LOW NOISE COANNULAR NOZZLE

The most promising method for reducing jet noise with minimum penalty to the propulsion system is based on unique exhaust features of the VSCE, combined with a coannular nozzle system. P&WA is conducting a test program under NASA sponsorship to evaluate this concept and to compare noise characteristics of various suppressor configurations. Based on test data, unsuppressed coannular nozzles have the potential for significant reductions in jet noise without the performance penalties and other burdens such as weight, cost and complexity associated with mechanical suppressors. This potential noise reduction is shown in Figure 5.1-1 for various levels of specific thrust. Based on coannular nozzles having unique velocity profiles similar to that shown in Figure 5.1-2, a significant reduction in jet noise has been measured and is shown in Figure 5.1-1 for the VSCE engine relative to SAE predicted noise levels. This profile is obtained through VSCE design features combined with unique throttle scheduling techniques for the combustors of the engine and bypass flow streams. Figure 5.1-3 illustrates the basic principle that provides this natural suppression for coannular nozzles. The left side of Figure 5.1-3 shows the velocity profile for a single stream nozzle. The right side shows a coannular nozzle. At the Station X downstream from the nozzle exit plane, the profile on the left for the single stream nozzle shows the effect of mixing and momentum exchange with ambient air. The shaded velocity profile indicates the maximum core velocity has not been reduced. For the coannular nozzle, the maximum velocity in the bypass stream is reduced by mixing and momentum exchange with air on both the outer and inner surfaces. The peak velocity has been reduced at the measuring Station X and jet noise is correspondingly lower. The net effect for the coannular nozzle is equivalent to an increase in BPR with a lower jet velocity and reduced noise for the overall engine. The next major step in evaluating the potential benefit of coannular nozzles is to determine the jet noise and performance characteristics at conditions that simulate flight velocities.

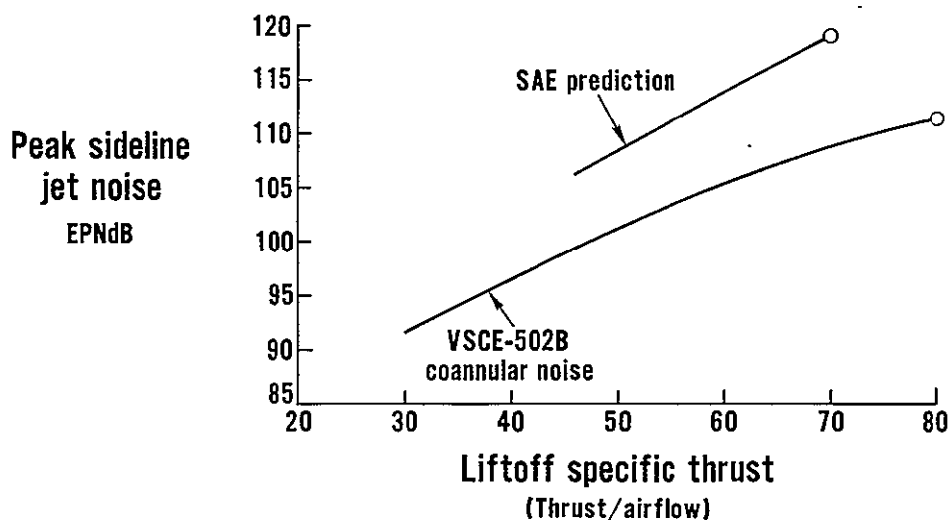


Figure 5.1-1 Potential Reduction in Jet Noise with Coannular Nozzles

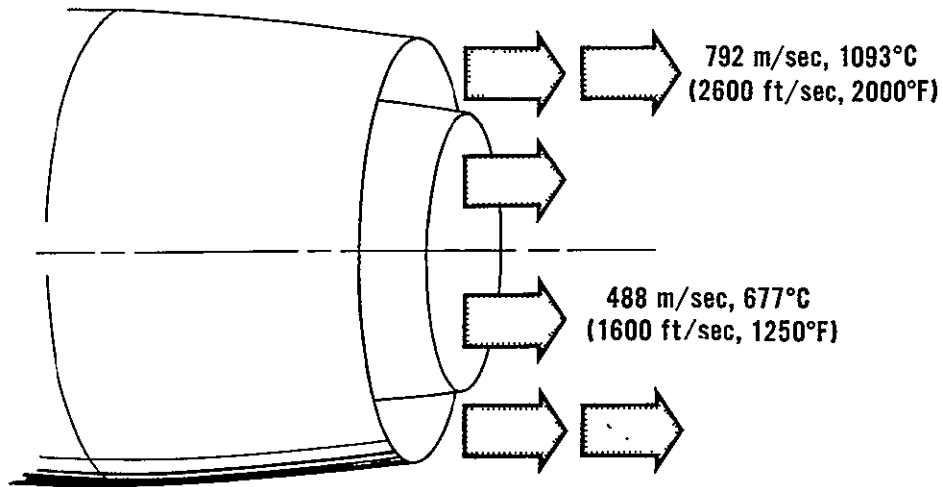


Figure 5.1-2 Coannular Nozzle Velocity Profile Required for Low Noise

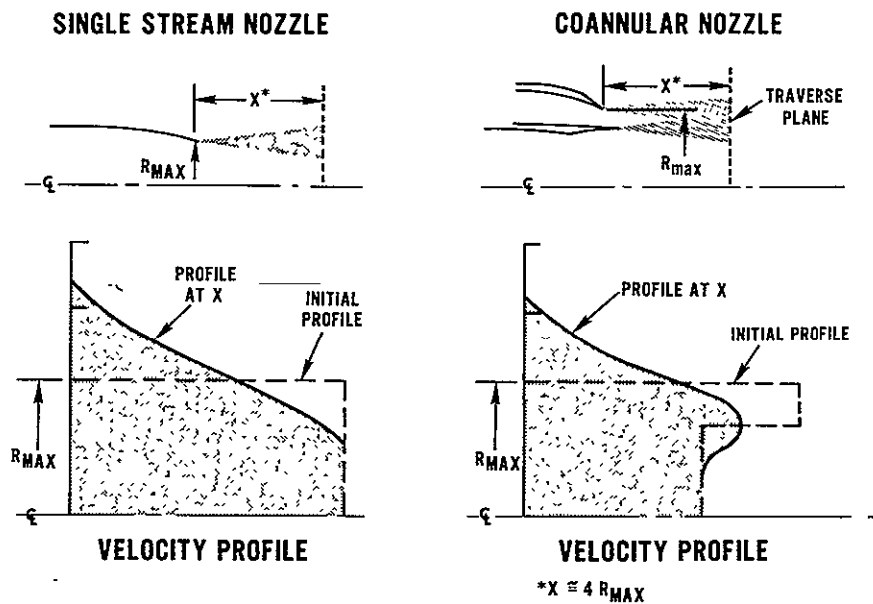


Figure 5.1-3 Comparison of Single Stream and Coannular Nozzle Velocity Profiles

Noise and performance testing of axisymmetric coannular nozzles is being conducted at P&WA in the five phases shown in Table 5.1-I. As indicated, the static test program and the wind tunnel test program have been completed, and the other two programs are being conducted.

TABLE 5.1-I

COANNULAR NOZZLE NOISE AND PERFORMANCE PROGRAMS

Static Test Program (1974-1975)

- Single-stream convergent nozzle (reference)
- Two-stream, coannular, axisymmetric nozzles
 - Two ratios of throat areas (0.75 and 1.2)
 - Hardwall ejector
 - Acoustically treated ejector
 - Suppressors-bypass stream only
 - Fingers
 - Chutes
 - Tubes

Wind Tunnel Test Program (1975-1976)

- Simulated flight speeds to 137 m/sec (450 fps)
- Nozzle conditions
 - Temperature from 121 to 427°C (250 to 800°F)
 - Pressure ratios from 1.3 to 3.2
- No suppressors

Effect of Nozzle Configurations on Jet Noise and Static Performance (1976-1977)

- Two-stream, coannular nozzles
 - Radial dimensions of outer nozzle annulus
 - Radial dimensions of inner nozzle
 - Axial displacement of throats

Nozzle Performance Tests (1977-1978)

- Simulated flight speeds for selected configuration
 - Subsonic cruise
 - Supersonic cruise

VCE Critical Technology Testbed Program (1978-1980)

The objectives of the last two programs in Table 5.1-I are: (1) to establish an empirical aero/acoustic design system for coannular nozzles, and (2) to incorporate the basic aero/acoustic findings into a realistic flight nozzle design and demonstrate nozzle performance at simulated key flight conditions.

The static test program established the aero/acoustic characteristics of VSCE coannular nozzles over a wide range of exhaust conditions. This program consisted of noise and thrust evaluation of two unsuppressed coannular nozzles and four multi-element coannular nozzle/suppressor configurations along with an equivalent convergent nozzle. The results of this program showed significant noise reductions for the coannular configurations relative to the convergent nozzle. Further noise reductions were obtained with the addition of an acoustically treated ejector. The wind tunnel test program confirmed the static test results, specifically, that coannular nozzles have a 60 to 8 dB jet noise advantage over conventional engines with a single stream exhaust system both having the same specific thrust.

To evaluate the effect of coannular nozzle configurations on jet noise and thrust, a series of scale models (approximately 1/12 size) has been tested statically to provide the additional data necessary to formulate a design system reflecting both noise and performance characteristics. Five unsuppressed coannular nozzle configurations were tested to expand the data base generated during the earlier programs. The model test configurations involve basic coannular nozzle dimensional variations so that the result will allow accurate assessment of the selected parameters, and permit application to the anticipated range of flight type exhaust systems consistent with VSCE concept. A brief study is being conducted to incorporate the above information into a refined nozzle design.

This aero/acoustic design system will be applied to the most promising nozzle concept for the VSCE. Acoustic trades will be integrated along with the requirements for high cruise performance, low weight and simplicity into a preliminary design layout of the exhaust system configuration. A 1/10 scale model of the resultant configuration will be tested at subsonic and supersonic conditions to establish nozzle performance.

Results from these nozzle programs will be used to design the coannular nozzle configuration for the VCE critical technology testbed program, which is described in Section 3.6.

5.2 LOW EMISSIONS DUCT-BURNER

The duct burner is a critical technology requirement for the VSCE concept. Duct burners are used to augment engine thrust during take-off and climb. For supersonic cruise, these augmentors are throttled back to low fuel/air ratios. Advanced combustion technology is required to provide low emissions and high efficiency without compromising the dimensions, complexity, and operating characteristics (stability, lean blow-out and combustion noise) of these duct burners. Because of the low noise feature of this engine, the duct-burner operating conditions are much different from conventional afterburners used for military engines. Primary burner concepts and configurations evaluated in the NASA-sponsored ECCP are not directly applicable to these duct burners because of the differences in air conditions (pressures, temperatures and flow rates) entering these burners. These differences in operating conditions, combined with the low emissions and noise, and high efficiency requirements, dictate the need for applied combustion research for these AST duct burners. The following three-phase program is in progress.

Phase 1 – Duct Burner Analytical Screening Program

Pratt & Whitney Aircraft completed in 1976 under NASA Contract NAS3-19781, an eight-month program to investigate low emissions duct burners. The objective of this study was, through systematic analytical screening, to identify advanced combustor concepts that have the potential for low emissions while meeting the stringent performance requirements and economic considerations dictated by the VSCE concept. The approach pursued in this study was to define various pilot and secondary stage concepts that ranged from current state-of-the-art technology to such advanced concepts as prevaporized-premixed systems. These concepts were screened on the basis of their potential emissions characteristics using, as a reference, data from such programs as: the NASA Experimental Clean Combustor Program (ECCP) and Can Annular Emissions Reduction Program, Pratt & Whitney Aircraft's related experience with main burners and augmentors, and the published results of investigations by NASA, other engine manufacturers and other research laboratories. Based on the results of this screening, a number of pilot-secondary stage concepts were combined to synthesize promising duct burner configurations. Further analysis, involving aerothermal sizing, refined emissions projections, and preliminary design studies, provided the data necessary to evaluate these concepts against such criteria as: emissions, performance, engine compatibility, and engine cost and weight. The study resulted in the definition of four concepts that appear, on the basis of these criteria, as most promising for further evaluation.

The final screening phase included an assessment of development risks. The concept selected for experimental evaluation in the next phase is an extension of the concept evaluated in the ECCP and therefore is a relatively low risk concept that requires only moderate level of advanced technology. Other advanced concepts were identified that require more analysis and basic research before applied studies and rig tests can be conducted.

Phase 2 – Experimental Evaluation of the Selected Duct Burner Concept

Based on results from the analytical screening program, a rig test program is in progress under NASA Contract NAS3-20602. The objective of this effort is to design, optimize and demonstrate the performance and emissions capabilities of the best moderate development risk concept identified in the screening study. This program serves the dual purpose of providing the necessary experimental qualification of the duct burner for the VCE Testbed Program while also providing experimental substantiation of the emissions and performance predictions made during the screening study.

This experimental rig program involves designing the duct burner in a size compatible with the fan stream of the VSCE concept. A two-dimensional segment rig version of this duct burner is being fabricated with the segment representing a fifty-five degree sector of the full annular duct burner. The rig will be tested in a facility capable of duplicating the fan stream pressure, temperature, and corrected flow per unit area of the VSCE at the simulated take-off operating point and also at supersonic cruise and transonic climb conditions. The test will be conducted over this range of conditions, and data obtained to define the emissions characteristics as well as duct burner performance parameters including cold and hot flow pressure loss, thrust efficiency, stability, lighting characteristics and propensity for acoustic instabilities. If successful, this experimental program will result in a well-defined, advanced-technology, low-emissions duct burner design.

Phase 3 – VCE Testbed Demonstration of the Selected Duct Burner Concept

Phase 3 of the overall duct burner program will involve experimental evaluation of a large-scale, duct-burner configuration in the VCE Testbed Program, described in Section 5.9.1.

5.3 DUCT BURNER NOISE PROGRAM RECOMMENDATION

With the possibility of using coannular nozzles to reduce jet noise, and sonic inlets to reduce fan noise propagating from the inlet, noise that is released from the fan duct and nozzle remains a potentially significant noise source. In particular, the effect of duct burner combustion on aft noise has not been established. An accurate evaluation of these potential noise sources is not possible at this time as procedures do not exist to predict duct burner noise or the effect of the duct burner on aft propagating fan noise. The objectives of this recommended program are to measure far field noise produced by a duct burner.

Noise tests will be conducted with the AST duct burner rig following the performance and emissions test programs described in Section 5.2. This rig hardware can be the same duct burner segment, and the tests would be performed in a P&WA outdoor combustion noise test facility. Far field noise data will be obtained while the rig is operated over a range of burner pressures, temperatures and corrected flow levels, with each of these parameters being varied independently. Internal instrumentation will be installed to obtain dynamic pressure (internal noise) measurements in the burning region.

An empirical prediction procedure will be established with data obtained from the duct burner noise experimental program. These data will be examined to determine the effects of burner inlet temperature, pressure, airflow rate and burner temperature rise on duct burner noise levels, spectra and directivity. The prediction models will be developed to reflect these results. The prediction model will then be used to estimate duct burner combustion noise for the VSCE concept.

5.4 VARIABLE GEOMETRY MULTI-STAGE FAN

Another critical technology requirement for the VSCE concept is a multistage fan with variable geometry. The fan program described in the Phase III Final Report (Ref. 3) is still a requirement.

5.5 LOW EMISSIONS PRIMARY BURNER

The P&WA Experimental Clean Combustor Program (ECCP) sponsored by NASA concentrated on advanced combustion concepts and designs for primary burners of subsonic engines in order to reduce emissions in both the airport environment and at high altitudes. An AST addendum to this program was conducted to reduce NO_x without compromising other burner requirements such as efficiency, stability, weight, cost and emissions characteristics at other operating conditions. Application of these results to AST study engines indicate further improvements are required to reduce emissions levels, especially in the airport vicinity. The reason for needing further improvements over advanced subsonic engines is due primarily to the differences between AST engine cycles and subsonic engine cycles. For example, the AST

engines have lower bypass ratios, lower overall pressure ratios, and employ augmentors. They also experience significantly higher inlet temperatures going into the main burner at supersonic cruise. The sensitivity between the level of NO_x that is generated during supersonic cruise in the stratosphere and cycle pressure ratio, plus the requirements for low emissions in the airport vicinity require advanced combustor technology for the VSCE primary burner as well as for the duct burners.

To further explore the emissions characteristics of advanced burner concepts for AST VCEs, a continuation of the work started during the ECCP AST Addendum is recommended. This would be an analytical and experimental program to control fuel/air mixtures and residence times in the hot combustion zones.

To reduce the cost of experimental programs in these areas, it may be possible to use existing hardware from the ECCP Phase II program or from other experimental burner programs.

5.6 HOT SECTION CRITICAL TECHNOLOGY REQUIREMENTS

Several critical technology requirements have been identified for the hot section of these AST engines. They are high temperature turbine airfoil materials (advanced directionally solidified alloys), high temperature end wall materials (ceramics), high creep-strength turbine disk materials, active tip clearance control technology, and high temperature burner liner material. The basic reasons that AST engines are very sensitive to these areas of hot section technology are:

- Projected turbine inlet temperatures are in the 1427°C to 1538°C (2600°F to 2800°F) range. At supersonic cruise, cooling air temperatures are in the 593°C to 704°C (1100°F to 1300°F) range. In this hot environment, current technology materials and cooling systems will require large quantities of cooling air, imposing a penalty on the cycle and turbine efficiency.
- The integrated stress-time-temperature requirements for AST turbines present more severe creep and oxidation conditions than do current technology subsonic engines.
- Cycle characteristics of the AST engines, namely low pressure ratios of the high spool, in conjunction with unique flow schedule of the engine during supersonic operation, cause high stresses in the turbine blading. This characteristics, along with the selected turbine blade material, sets the maximum design speed for the high spool which, in turn, dictates the elevation and number of stages in the compressor.

The program recommendations for the VSCE hot section, summarized in the Phase III Final Report (Ref. 3), are still required.

5.7 ELECTRONIC CONTROL SYSTEM

A full-authority, digital, electronic control system is a critical technology requirement for the VSCE concept. The eight control system variables listed in Table 5.7-I are a convincing indication that hydromechanical controls would result in an expensive and heavy system which cannot properly fulfill the control function. In contrast with these eight variables, current-technology subsonic commercial engines have only three basic control system variables. For the more complex VSCE, a full-authority digital electronic control system has the potential for numerous improvements relative to an equivalent hydromechanical system. These potential benefits are listed in Table 5.7-II.

TABLE 5.7-I

VSCE PROPULSION SYSTEM CONTROL REQUIREMENTS

- Variable geometry inlet
- Variable geometry fan
- Variable geometry compressor
- Primary burner fuel flow
- Duct burner fuel flow
- Variable duct nozzle
- Variable engine nozzle
- Reverser/ejector system

TABLE 5.7-II

POTENTIAL BENEFITS FOR AST ENGINE ELECTRONIC CONTROL SYSTEM

- Better control accuracy — improved performance.
- Reduced cost and weight.
- Automatic rating schedules.
- Improved maintainability from quick mount computer designs and printed circuit modules.
- Flexibility to reprogram during development.
- Digital data links facilitate integration with inlet control, condition monitoring system, and power management system.
- Self testing capability.
- Self trim capability.

Pratt & Whitney Aircraft is presently conducting extensive research and development activity in the area of electronic controls. It is difficult to isolate a portion of this overall effort that has unique meaning to AST engines. Instead, a study program is recommended. This program is subdivided into four tasks:

- Study of closed loop control of convergent-divergent nozzles for optimum performance
- Definition and evaluation of an integrated airplane/engine control system
- Cost effectiveness studies of a VSCE condition monitoring system
- Study of methods for experimentally determining reliability of the electronic control system

5.8 PROPULSION SYSTEM PRELIMINARY DESIGN AND INTEGRATION STUDIES

The integration work accomplished during Phase IV provides the foundation for more detailed studies of the VSCE, including preliminary design of the complete engine, and continuation of the integration studies.

5.8.1 Integration Studies

In Section 3.5.8 of the Phase III Final Report (Ref. 3), integration work in a variety of areas was recommended. These recommendations remain valid; however, Phase IV results indicate emphasis should be on:

- Inlet/Engine System
- Nozzle/Reverser System
- Airframe/Engine Interfaces

Sensitivity and trade studies conducted as part of this follow-on integration work will lead to the optimum engine/inlet system. These trade studies will concentrate on establishing the design requirements for the inlet. These requirements would include variable geometry needs, performance, bleed systems, structural/mechanical considerations, stability/distortion characteristics, and noise control constraints.

Similarly the nozzle/reverser system trade studies would lead to the optimum nozzle system and would cover establishing the requirements for reverser targeting and effectiveness, mechanical/structural arrangement, and acoustic treatment payoff.

Additional integration studies are recommended in the area of engine/airframe interfaces. These include the definition of requirements, and the development of designs to meet these requirements in the areas of secondary flow systems, fuel/oil/air thermal management systems, engine/airframe accessories, integrated control systems, engine mounting and pod design. Integration efforts focusing on these areas will provide the basis for optimizing the VSCE/airframe system.

In another area associated with optimizing the installed engine, operational ratings (airflow and thrust scheduling) of the VSCE will be further defined in order to meet specific requirements such as those dictated by inlet operation, noise considerations or airframe performance trade-offs. A special consideration to be included in these integration studies is a more detailed evaluation of programmed throttle scheduling for noise abatement. This effort would include preliminary design of integrated engine/airplane control systems to provide the optimum propulsion system performance and minimal environmental impact over the entire flight spectrum.

5.8.2 Preliminary Design

The second area of refinement studies of the VSCE should be in preliminary design. This will compliment the on-going VCE technology programs by expanding the critical technology requirements of the VSCE. A more detailed aerodynamic, mechanical and thermal definition of each engine component is required to fully assess structural integrity, manufacture and assembly characteristics, maintenance requirements, key variable geometry components and engine cost.

5.9 VCE EXPERIMENTAL PROGRAMS

In addition to identifying critical technology requirements and recommending related programs, programs are underway for evaluating and demonstrating these technologies in experimental engines. The basic objective is to integrate the critical technologies into a large scale engine configuration in order to demonstrate overall benefits, characteristics, and interactions of the selected technologies.

5.9.1 VCE Critical Technology Testbed Program

The VCE critical technology Testbed Program has been defined for minimum cost and entails demonstrating the critical environmental technologies for the VSCE concept. The objective of this program is to demonstrate, in a large-scale engine environment, the noise and thrust characteristics of a coannular nozzle with an inverted velocity profile, and the emissions, performance and noise characteristics of an advanced duct-burner design. For this approach, experimental configurations of critical components would be applied to an existing engine. Candidate P&WA engines that were considered for demonstrating these critical technologies are the F100, the TF30 or the TF33. The F100 has been selected. It is planned to be modified for two separate flow streams, the engine stream and the bypass stream, and can accommodate an experimental duct burner and a coannular nozzle system. These modifications can be accomplished without affecting the rotating machinery and support structure of the F100. Modifications to the existing engine control system will be made to provide separate throttle control for the primary burner and the duct burner. This will allow testing over a broad range of jet exhaust temperatures and velocities to evaluate the coannular noise benefit and corresponding emissions levels.

Figure 5.9-1 shows the basic testbed arrangement. This Testbed Program will be preceded by separate duct burner and nozzle analytical and experimental programs described in Sections 5.1 and 5.2 to provide the baseline designs of these unique components. This Testbed Program will be conducted in existing facilities that are suitable for measuring noise and emissions over a range of engine and duct burner power settings. Table 5.9-I lists the specific objectives of the program.

TABLE 5.9-I

VCE CRITICAL TECHNOLOGY
TESTBED PROGRAM OBJECTIVES

- Determine the coannular nozzle noise benefits with large-scale engine over a broad set of operating conditions simulating take-off and landing power settings.
- Evaluate emissions and performance characteristics of a large-scale duct burner over a wide range of fuel/air ratios and simulated VCE conditions.
- Evaluate the overall compatibility of a multi-stage fan, a low emissions duct burner and a coannular nozzle and ejector system designed for low jet noise.
- Evaluate the noise characteristics of a duct burner.
- Evaluate the influence of the duct burner on aft propagating fan noise.
- Determine the effectiveness of acoustic treatment in the fan duct and along the ejector/nozzle surfaces.
- Evaluate stability characteristics between the engine the duct burner, and the variable geometry nozzle.
- Measure the sensitivity of ejector configurations on jet noise and possibly on nozzle performance.
- Determine the level of turbine noise and other core noise sources relative to fan and jet noise levels.
- Demonstrate some of the VSCE cycle characteristics such as the inverse throttle schedule and operating the fan at maximum flow but partial pressure ratio for noise reduction.

This Testbed Program would be extended further by evaluating the areas listed in Table 5.9-II.

TABLE 5.9-II
ADDITIONAL AREAS FOR
EVALUATION IN TESTBED PROGRAM

- Evaluate flight effects on the coannular noise benefit by testing a large wind tunnel.
- Evaluate emissions and performance characteristics of a refined duct burner designs.
- Evaluate a coannular nozzle and ejector system that is optimized for the VSCE and is a more exact configuration of a flight design than the initial configuration.
- Adapt the nozzle/ejector system to include a thrust reverser for noise, effectiveness and stability testing. This could be done statically and in simulated flight by testing in a large wind-tunnel.
- As back-up to the coannular noise benefit, a mechanical jet noise suppressor could be added to the high velocity bypass stream.
- Evaluate a variable geometry supersonic inlet for noise, stability and transient characteristics.
- Include an integrated electronic control system to evaluate overall transient and stability characteristics.
- Evaluate military technology requirements such as low weight coannular nozzles designed for low infrared signatures.

Approaches are being evaluated to include other areas of critical technology that could be evaluated and verified in an overall VCE Experimental (VCEE) Program. These could include:

- Evaluation of the aero/acoustic characteristics of a variable geometry multi-stage fan designed specifically for the requirements of the VSCE.
- Compatibility testing of this multi-stage fan with a supersonic inlet designed for low noise with near-sonic internal Mach numbers during take-off and approach. This could include measuring distortion sensitivity and stability characteristics.
- A low emissions primary burner designed for a high temperature environment.
- A high speed, single-stage, high-pressure turbine.
- Advanced cooling and sealing technology systems for the high pressure turbine.
- High temperature materials associated with the high spool components.

TABLE 5.9-II (CONTINUED)

- Advanced rotor support concepts that remove bearing compartments from the hot section of the engine.
- Demonstrate commercial engine life characteristics of the hot section incorporating the VCE inverse throttle schedule.
- An advanced, high speed, low-pressure turbine.

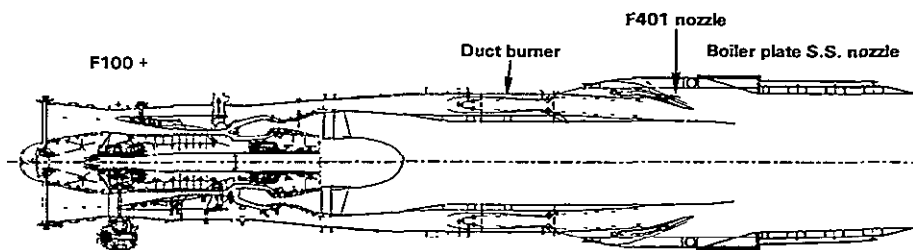


Figure 5.9-1 Conceptual Arrangement of Testbed Engine

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LIST OF ABBREVIATIONS

A_c	Inlet lip area
A_o	Inlet freestream area
AST	advanced supersonic technology
BPR	bypass ratio
$^{\circ}\text{C}$	degrees Celsius
CET	combustor exit temperature
CDT	compressor discharge temperature
C_D	drag coefficient
CG	center of gravity
CO	carbon monoxide
C_v	nozzle velocity coefficient
dB	decibels
ECS	environmental control system
EI	emissions index
EPA	Environmental Protection Agency
EPAP	Environmental Protection Agency Parameter
EPNdB	effective perceived noise decibels
EPNL	effective perceived noise level
$^{\circ}\text{F}$	degrees Fahrenheit
FAR-36	Federal Aviation Regulation - Part 36
F_n	net thrust
$F_{N\text{COMM}}$	net thrust at community noise measuring point
F_{NTD}	net thrust at 360 km/hr (200 Kts)

LIST OF ABBREVIATIONS (Cont'd)

F_{TOC}	flap angle during take off climb
fps	feet per second
h	height, altitude
H_{COMM}	Altitude at community noise measuring point
HPT	high-pressure turbine
ISA	International Standard Atmosphere (1962)
KEAS	knots equivalent air speed
hr	hour
in	inch
kg	kilograms
km	kilometers
kN	kilonewton
lbf	pounds, force
lbm	pounds, mass
L/D	lift to drag ratio
m	meters
LPT	low-pressure turbine
MAX	maximum
MCR	maximum climb rate
MDC	McDonnell Douglas Corporation
MEW	manufacture empty weight
MIN	minimum
Mn, M	Mach number

LIST OF ABBREVIATIONS (Cont'd)

N	Newton
n. mi	nautical mile
NO _x	oxides of nitrogen
N/R	nozzle reverser
OEW	operational empty weight
OPR	overall pressure ratio
PSGR	passenger
°R	degrees Rankine
PTO	power takeoff
SCAR	Supersonic Cruise Airplane Research
sec	second
T _{amb}	ambient temperature
TCA	turbine cooling airflow
THC	— total hydrocarbons (unburned)
TO	take-off
TOGW	take-off gross weight
TSFG	thrust specific fuel consumption
VCE	variable cycle engine
ΔV _{CLIMB}	Velocity gained during take-off climb
V _{LOF}	Airplane velocity at lift-off
V _{jd} /V _{je}	velocity ratio of duct burner nozzle velocity/engine jet velocity
VSCE	variable stream control engine
W _{at}	total airflow
W _{at2}	inlet corrected airflow

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